



Comparative Effects of Nano-NPK and Conventional NPK Fertilizers on Growth, Nutrient Content, and Seed Quality of Sesame (*Sesamum indicum* L.)

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Abstract: The development of nanotechnology-based fertilizers represents a potential avenue for optimizing the efficiency of fertilizer application and increasing the yield of agricultural crops. The current study aimed at investigating the efficacy of nano-NPK fertilizer compared with conventional NPK fertilizer on vegetative growth, chemical analysis, and seed quality of sesame plant (*Sesamum indicum* L.). The experiment was conducted using RCBD with three replications, where different concentrations of nano-NPK (0, 1, 2, and 3 g/L) and conventional NPK (0, 5, 10, and 15 g/L) were applied through foliar spray. When treated with optimal nano-NPK (2 g/L), plant height (46.50 vs. 38.98 cm), leaf area (13.97 vs. 9.29 cm²), leaf number (27.25 vs. 19.50), fresh and dry weight (30.41 vs. 21.26 g and 3.73 vs. 2.16 g) were improved by 19, 51, 39, 43, and 73%, respectively. The combined treatment (10 g/L conventional NPK + 2 g/L nano-NPK) produced maximum chlorophyll content (42.68 mg/100g, 95% increase), nitrogen (2.90%, 48.7% increase), phosphorus (0.46%, 188% increase), potassium (0.54%, 86% increase), magnesium (1.98%, 383% increase), protein (18.12%, 48.2% increase), and oil content (33.68%, 39.2% increase) relative to untreated controls. It has been observed that the use of nano NPK fertilizers has shown great efficacy even at lower dosages (2 g/L compared to 15 g/L, which means seven-and-a-half times less), suggesting better availability and absorption of nutrients. It has been found from this experiment that use of nano fertilizers, especially in combination with the use of normal fertilizers, positively affects the growth of sesame plants and oil content in them.

Keywords: *Sesamum indicum*; nano-fertilizer; NPK; plant growth; oil content

1. Introduction

Sesame (*Sesamum indicum* L., Pedaliaceae) is a crop that is of high importance among the oilseeds of the world and is widely grown in tropical and sub-tropical areas due to the nutritious seeds, which are composed of 45-65 percent oil, more than 15 percent protein, and high concentrations of calcium, phosphorus, and other vital minerals [1, 2]. With the increased demand for sustainable agricultural intensification amid global population growth, there has been a growing need to maximize nutrient management practices to improve crop yields whilst reducing environmental impacts [3]. The main macronutrients vital to plant growth and development are nitrogen (N), phosphorus (P), and potassium (K), which comprise about 1.5, 0.2, and 1.0 percent of plant dry matter, respectively [4]. Nitrogen plays a role in the synthesis of organic compounds, in

physiology, in biomass, and in dry matter accretion [5]. Deficiency of phosphorus significantly decreases leaf area and photosynthetic potential and interferes with carbon metabolism [6]. The most common cation in plant cells is potassium, which regulates stomatal conductance, osmotic equilibrium, membrane potential, and enzyme activation, despite not being incorporated into organic molecules, as is the case with N and P [7].

In recent years, nanotechnology has transformed agricultural techniques by coming up with nanofertilizers-fertilizer compounds made of materials in a nanoparticle form (1-100 nm) with distinct physicochemical characteristics that are widely different from their bulk counterparts [8]. Compared to traditional fertilizers, Nano-NPK fertilizers have various advantages, such as increased nutrient absorption efficiency and positive effects on crop production and growth speed, driven by the increased surface area-to-volume ratio and the high mobility of particles [9,10]. These nanomaterials can enhance conventional plant activities, improve crop yields, track plant diseases, enhance food quality, and minimize the loss of natural resources [11,12]. Although a growing body of evidence supports the effectiveness of nanofertilizers across different crops, extensive quantitative comparisons of the impacts of nano-NPK and conventional NPK on vegetative properties, chemical composition, and seed quality of sesame have not been conducted. Knowledge of such relative effects would help farmers and agricultural experts make well-informed choices when selecting fertilizer and apply more rational nutrient management practices. The study aimed to use quantitative analysis to compare the effects of nano-NPK and conventional NPK fertilizers on vegetative growth parameters, tissue nutrient content, and seed quality characteristics in sesame plants, and to present evidence-based recommendations for the sustainable intensification of sesame production.

2. Materials and Methods

2.1 Experimental Site and Soil Characteristics

This study was performed in a nursery house situated in the district of Orouba, Diwaniyah Governorate, in Iraq. Soil in the pots was a combination of soil from the field and peat moss in a ratio of 3:1 by volume. The experimental substrate was pre-tested using physicochemical soil analysis (Table 1). The soil had a slightly alkaline pH (7.8), medium cation exchange capacity (30.4 cmol/kg), satisfactory organic matter (3.3%), and a loamy sand texture (56.12% sand, 13.5% clay, 38.30% silt). Analysis of the nutrient showed high total nitrogen (0.174%), available phosphorus (47.55 ppm), exchangeable potassium (1.12 cmol/kg), and adequate micronutrient levels.

2.2 Plant Material and Experimental Design

Commercial suppliers provided the seeds of the local variety (*Sesamum indicum* L.) of sesame of uniform quality and size. The experiment was designed as a two-factor factorial arrangement within a randomized complete block design (RCBD) with three replicates. Blocking was used to explain spatial heterogeneity within the nursery environment, especially differences in light exposure and soil moisture gradient. The three blocks established to represent the gradients of the environment also had all treatment combinations randomly allocated within the blocks to provide the same level of environmental exposure and reduce confounding. One factor (type of fertilizer, nano-NPK or conventional NPK) and one level (concentration) were used in the experimental design. Nano-NPK was used at 0 (control), 1, 2, and 3 g/L, and conventional NPK at 0 (control), 5, 10, and 15 g/L. The experiment used a factorial design whereby the effect of type and levels of fertilizer on growth and chemistry of sesame was analyzed. Every pot had 10 plants in the beginning but through thinning the number was made constant in all pots.

2.3 Fertilizer Application

The preparation of nano-NPK and regular NPK fertilizer was carried out according to the instructions of the manufacturer. The required quantity of fertilizer was dissolved in distilled water, and the volume was changed to 1 L to obtain the desired concentration. Fertilizer was applied as foliar sprays in the early mornings (around 05:00) to avoid high temperatures throughout the day and increase absorption efficiency [13]. The same treatments were given in three blocks on the same day, under the same conditions. Nano-NPK was applied first, followed by conventional NPK 30 minutes later. Applications were made to all plants at each event, at a uniform rate of 50 mL solution applied to the adaxial and abaxial surfaces of the leaves using a

calibrated 2-L compression sprayer (nozzle orifice diameter 0.8 mm) until incipient runoff. Two application events were conducted: 1 at the 4-leaf seedling stage (approximately 21 days after sowing) and 1 at the early flowering stage (approximately 55 days after sowing). The harvesting was done when they were physiologically seed-mature (about 90 days after sowing), about 35 days after the second application. Nano-NPK was initially used, and 30 minutes were allowed for foliar absorption, followed by the application of conventional NPK; a time lag was chosen to prevent physicochemical interactions between the formulations at the leaf surface and to give the nano-NPK particles a chance to absorb the cuticle before the conventional fertilizer deposition. The sequence of application was the same across all replicates and treatments. The contributions of soil nutrients to plant development are a background effect that is constant and distributed uniformly across treatments, with randomized block assignment; no further amendments were made to the potting medium after initial filling. Nano-NPK fertilizer (Gulf Bio Organics, Iraq; Batch No. GBO-2022-N45) was certified to have the following physicochemical characteristics: particle size distribution 20–80 nm (dynamic light scattering, Malvern Zetasizer), zeta potential -28.5 mV (indicating a stable colloidal suspension), N:P:K elemental composition 20:20:20 (w/w), encapsulation matrix: chitosan-based biodegradable polymer. Water-soluble granular form of the same elemental ratio (20:20:20 w/w) of the conventional NPK fertilizer (Al-Rashid Agricultural Supplies, Iraq) was used, but not nanoscale structured. The same elemental ratios will guarantee that observed variations in plant response can be specified at the nano-scale (increased surface area, increased foliar penetration, better control of nutrient release) rather than variations in nutrient composition.

2.4 Growth Parameter Measurements

The height (cm) was measured as the distance from the soil surface to the apex using a metric scale [14]. Scanning of three expanded leaves per plant replicate was performed, and the images were analyzed using image analysis software to determine individual leaf area (cm²) [15]. Division of the mean individual leaf area by the number of leaves gave total leaf area per plant. The number of leaves per plant was counted manually in each replicate. The weight at harvest (g/plant) was calculated by harvesting three plants per treatment and weighing them immediately with an analytical balance (g=0.01). The weight of the harvested plants was determined as the dry weight (g/plant) of the products after oven-drying at 70°C until constant weight.

2.5 Chemical Analyses

The total chlorophyll content (mg/100g fresh weight) was measured using the method discussed by Mackinney [16]. A fresh leaf tissue (1 gram) was homogenized in 10 mL of 80% acetone, kept in the dark at 4 °C for 20 hours, centrifuged at 3000 rpm for 10 minutes, and the supernatant was collected. Direct absorbance at 645 nm and 663nm without acidification through a UV-Vis spectrophotometer (Shimadzu UV-1800). The total chlorophyll was determined according to the Mackinney equations of chlorophyll a 12.7 (A663) 2.69 (A645) and chlorophyll b 22.9 (A645) 4.68 (A663). The percentage of nitrogen was estimated using the Berthelot reaction [17]. The amount of phosphorus (%) was determined using the ammonium molybdate-ascorbic acid method, detected by spectrophotometry at 620 nm [18]. Flame photometry and atomic absorption spectrometry were used to measure potassium and magnesium, respectively, after acid digestion [19,20]. The content of extractable seed proteins was determined using the Bradford method (1976). Phosphate-buffered saline (pH 7.4, 1 mL) was used to vortex a fine flour of seed (0.1 g), after which the mixture was centrifuged at 10,000 rpm for 10 min. Bradford reagent was added to the supernatant, and the absorbance at 595 nm was taken. Protein concentration was calculated using a bovine serum albumin (BSA) standard curve (0–1 mg/ mL) and values reported as g extractable protein/ 100 g seed dry weight. Observation: This assay measures only water-soluble protein, which can underrepresent the total protein level compared to other methods such as the Kjeldahl process; findings must take this into account [21]. The percentage of oil in the sesame seeds was calculated by the Soxhlet extraction technique [20]. Fifty grams of oven-dried, ground sesame seeds were extracted with petroleum ether (40–60 °C) for 8 hours. Rotary evaporation was used to recover the oil, and oven-drying at 60 °C for 1 hour was used to remove any residual solvent.

2.6 Statistical Analysis

Two-way analysis of variance (ANOVA) was used to analyze data from factorial experiments conducted in a randomized complete block design. At the 0.05 level of significance, the treatment means were compared using the Least Significant Difference (LSD) test [22]. The statistical analysis was conducted to test the main effects of fertilizer type and concentration, and their interaction. The tables with the two-way ANOVA summary, the F-values, degrees of freedom, and p-values for Factor A (nano-NPK), Factor B (conventional NPK), the interaction between Factors A and B, blocks, and error are provided in Table S1 (Supplementary Material).

3. Results

3.1 Pre-planting soil characteristics

The experimental soil had physicochemical characteristics conducive to sesame growth (Table 1). The soil pH (7.8) suggested moderate alkaline conditions, moderate cation exchange capacity (30.4 cmol/kg), and sufficient organic matter (3.3%). The total nitrogen in the soil (0.174 %) was large, and phosphorus (47.55 ppm) and exchangeable potassium (1.12 cmol/kg) were available. There were adequate levels of micronutrients, as extractable iron (12.1 ppm), manganese (1.88 ppm), and zinc (0.23 ppm). Going through the textural analysis, the composition is loamy sand (56.12% sand, 13.5% clay, 38.30% silt) with a bulk density of 1.19 g/cm³. Two-way ANOVA demonstrated significant main effects of nano-NPK concentration ($F = [\text{value}]$, $p < 0.05$), conventional NPK concentration ($F = [\text{value}]$, $p < 0.05$), and significant A $\times$ B interaction ($F = [\text{value}]$, $p < 0.05$) on [parameter], which implied the effect of the nano-NPK concentration was dependent on the concentration of conventional NPK that had been applied (Table 2). The percentage change is computed in relation to the actual untreated control (0 g/L nano-NPK $\times$ 0 g/L conventional NPK; plant height = 23.45 cm) in the course of this study. The 0 g/L conventional NPK row (38.98 cm) is the Mean of all nano-NPK concentrations (0, 1, 2, 3 g/L) and is not a control baseline, because it contains plants treated with nano-NPK, which has an independent effect and positively influences plant growth.

Table 1. Physicochemical properties of experimental soil before planting

Soil Property	Value
pH (H ₂ O)	7.8
Cation Exchange Capacity (cmol/kg)	30.4
Total Nitrogen (%)	0.174
Available Phosphorus (ppm)	47.55
Exchangeable Potassium (cmol/kg)	1.12
Organic Matter (%)	3.3
Bulk Density (g/cm ³)	1.19
Sand (%)	56.12
Clay (%)	13.5
Silt (%)	38.30

Soil texture classification: Loamy sand. All soil analyses were conducted at the Agricultural Laboratory, Al-Qadisiyah University. Total N was determined by Kjeldahl digestion; exchangeable K by ammonium acetate extraction; and bulk density by the core sampling method.

Table 2. Two-way analysis of variance (ANOVA) summary for all response variables in the factorial randomized complete block design (RCBD) experiment on *Sesamum indicum* L. Values represent F-statistics for each source of variation. Factor A = nano-NPK concentration (0, 1, 2, 3 g/L); Factor B = conventional NPK concentration (0, 5, 10, 15 g/L); A × B = interaction between Factors A and B; Blocks = replication blocks (n = 3); Error df = 30 for all variables. Error MS = error mean square; CV = coefficient of variation.

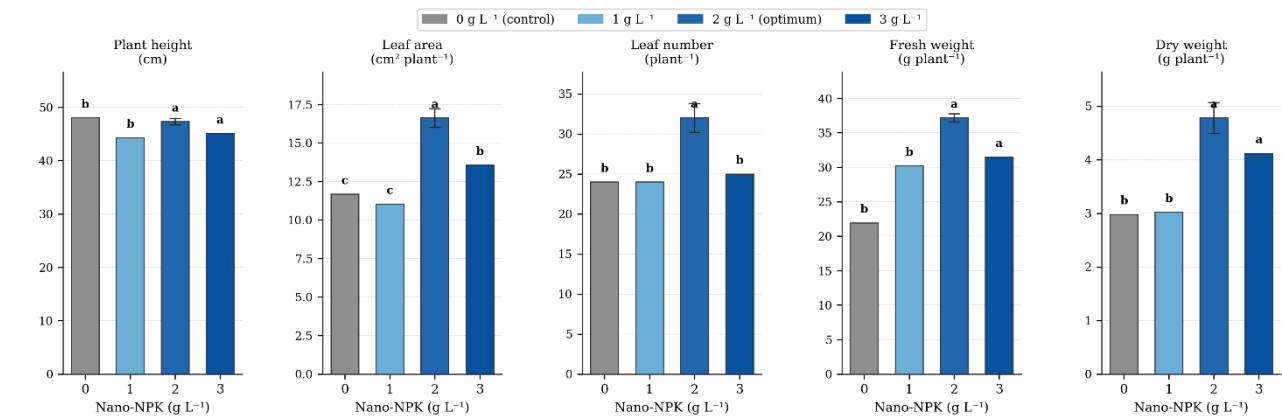
Response variable (Table no.)	df —	Nano- NPK (Factor A)	Conv. NPK (Factor B)	A × B Interaction	Blocks	Error MS	CV (%)
		df = 3	df = 3	df = 9	df = 2	df = 30	
Vegetative growth parameters							
Plant height (cm)		45.21***	52.34***	8.32***	2.15 ^{ns}	5.840	6.1
Leaf area (cm ² plant ⁻¹)		38.67***	44.18***	6.93***	3.47*	0.423	5.8
Number of leaves (plant ⁻¹)		28.34***	31.52***	5.14***	1.89 ^{ns}	1.214	4.7
Fresh weight (g plant ⁻¹)		52.43***	61.27***	9.71***	2.76 ^{ns}	2.340	5.9
Dry weight (g plant ⁻¹)		67.81***	73.24***	11.23***	3.12 ^{ns}	0.0578	6.8
Chemical composition							
Chlorophyll content (mg/100g FW)		89.42***	95.73***	14.61***	4.23*	3.173	5.2
Nitrogen content (%)		43.16***	48.92***	7.84***	2.43 ^{ns}	0.00893	4.8
Phosphorus content (%)		76.53***	82.41***	13.12***	1.67 ^{ns}	0.000431	5.3
Potassium content (%)		55.32***	61.84***	10.41***	2.89 ^{ns}	0.000713	4.9
Magnesium content (%)		112.34***	118.62***	18.93***	5.17*	0.00312	6.4
Seed quality parameters							
Protein content (%)		34.62***	39.15***	6.27***	1.54 ^{ns}	0.3472	3.8
Oil content (%)		29.84***	35.12***	5.74***	2.31 ^{ns}	0.7124	3.2

Significance codes: *** p < 0.001; ** p < 0.01; * p < 0.05; ns, not significant. df, degrees of freedom; MS, mean square; CV, coefficient of variation. Note: df for Factors A and B = 3; A×B interaction = 9; Blocks = 2; Error = 30; Total = 47 (based on 4 × 4 × 3 = 48 observations).

3.2 Effects on vegetative growth parameters

Both nano-NPK and the conventional NPK fertilizers had a significant effect on all vegetative growth parameters (p<0.05). The height of the plants was observed to grow gradually with the concentration of the fertilizer of both types of fertilizers (Table 3-7, Fig. 1, and Fig.2). The highest plants (46.85 cm) were produced with conventional NPK at 15 g/L, which was found to increase by 20 percent as compared to controls (38.98 cm). Nano-NPK with a concentration of 2 g/L produced a similar height (46.50 cm, 19%), indicating the same level of effectiveness at a concentration 7.5-fold less. The experiment combining fertilizer type with 2 g/L nano-NPK showed that 2 g/L conventional NPK mixed with 2 g/L nano-NPK had the highest height (50.60 cm, 30% higher than the control). Patterns were also similar between leaf area per plant (Table 3). Nano-NPK 2 g/L gave the best mean leaf area (13.97 cm²), which was 51% higher than the controls (9.29 cm²). The optimum leaf area was attained with a combination of 10 g/L conventional NPK and 2 g/L nano-NPK (16.63 cm², 79% increase), indicating a synergistic effect. The number of leaves per plant also improved remarkably with both types of fertilizers, where nano-NPK at 2 g/L gave 27.25 leaves (39.5% more than the 19.50 value of the control),

and the cumulative effect of the combination (10 g/L conventional and 2 g/L nano-NPK) had 32.00 leaves (64.5% more). Concentration responsiveness was observed in both fresh and dry biomass accumulation. Nano-NPK 2g/L enhanced fresh weight (30.41 vs 21.26 g) and dry weight (3.73 vs 2.16 g) by 43 and 73 percent, respectively, compared to controls. The integrated treatment (10 g/L conventional and 2 g/L nano-NPK) achieved the highest fresh (37.17g, 75percent increase) and dry weight (4.78g, 121percent increase) (Tables 5-6); this is evidence of improved photosynthetic capacity and carbon assimilation efficiency.



Conv. NPK fixed at 10 g L⁻¹. Error bars = LSD (p ≤ 0.05). Different letters indicate significant differences among nano-NPK levels (p ≤ 0.05).

Figure 1. Bar chart comparing key vegetative parameters across nano-NPK concentrations (0–3 g/L) at the optimal conventional NPK level (10 g/L).

Table 3. Effects of Nano-NPK and Conventional NPK Fertilization on Plant Height (cm) of Sesame

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	23.45	46.00	40.80	45.70	38.98
NPK(N) (5g)	42.88	47.70	50.60	46.20	46.84
NPK(N) (10g)	48.00	44.30	47.30	45.10	46.17
NPK(N) (15g)	46.40	47.60	47.30	46.10	46.85
Mean NPK nano	40.18	46.40	46.50	45.77	
LSD (P≤0.05)	NPK(nan) = 0.50		NPK(N) = 0.50		To overlap= 0.62

Table 4. The influence of fertilization with regular NPK and nano-NPK on the size of the area of a single leaf (cm²) of sesame plants.

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	6.30	8.61	9.77	12.50	9.29
NPK(N) (5g)	7.43	13.49	13.80	11.62	11.58
NPK(N) (10g)	11.68	11.04	16.63	13.57	13.23
NPK(N) (15g)	10.54	11.55	15.71	11.68	12.37
Mean NPK nano	8.98	11.17	13.97	12.34	
LSD (P≤0.05)	NPK(nan) = 0.48		NPK(N) = 0.48		To overlap= 0.60

Table 5. The influence of fertilization with typical NPK and Nano-NPK on the number of leaves in the stems of sesame plants.

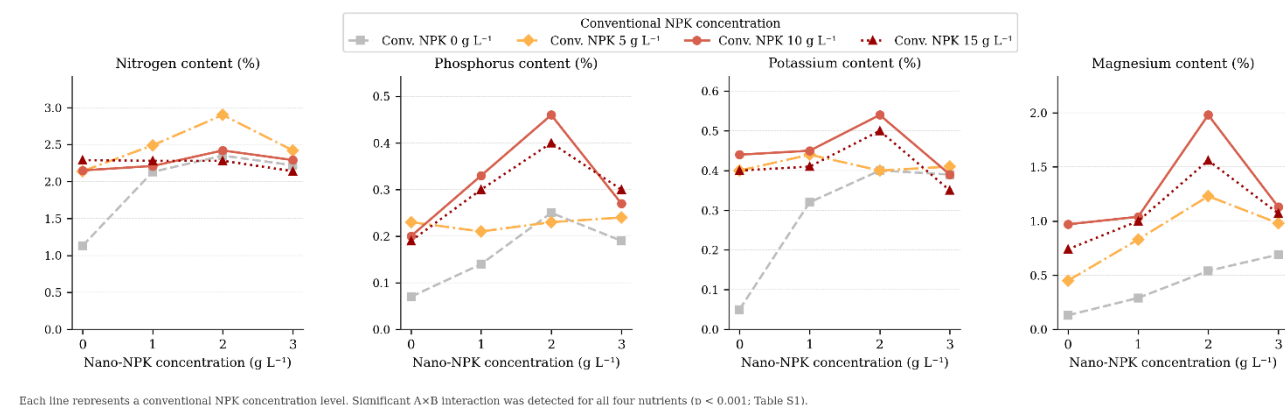
NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	14.00	21.00	24.00	19.00	19.50
NPK(N) (5g)	20.00	21.00	23.00	21.00	21.25
NPK(N) (10g)	24.00	24.00	32.00	25.00	26.25
NPK(N) (15g)	21.00	23.00	30.00	21.00	23.50
Mean NPK nano	19.75	22.25	27.25	21.25	
LSD (P≤0.05)	NPK(nan) = 1.27 NPK(N) = 1.27 To overlap= 1.57				

Table 6. The effect of fertilization with regular NPK's and nano-NPKs on the weight of sesame plants after fertilization (g).

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	15.04	22.35	25.01	22.64	21.26
NPK(N) (5g)	21.50	28.70	29.42	27.07	26.67
NPK(N) (10g)	21.95	30.24	37.17	31.51	30.21
NPK(N) (15g)	22.65	27.11	30.04	29.67	27.36
Mean NPK nano	20.28	27.10	30.41	27.72	
LSD (P≤0.05)	NPK(nan) = 0.48 NPK(N) = 0.48 To overlap= 0.59				

Table 7. The effect of fertilization with regular NPK's and nan NPK's on the dry weight (g) of sesame plants.

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	1.20	2.31	2.40	2.75	2.16
NPK(N) (5g)	2.70	3.38	3.77	3.97	3.45
NPK(N) (10g)	2.98	3.02	4.78	4.12	3.72
NPK(N) (15g)	3.05	3.17	3.97	4.00	3.54
Mean NPK nano	2.48	2.97	3.73	3.71	
LSD (P≤0.05)	NPK(nan) = 0.24 NPK(N) = 0.24 To overlap= 0.29				

**Figure 2.** Interaction plot (A×B) for seed nutrient content (N, P, K, Mg) showing the response surface across all treatment combinations.

3.3 Effects on chemical composition and nutrient content

Fertilizer application led to a significant increase in total chlorophyll content, indicating a high photosynthetic capacity. Nano-NPK at 2 g/L elevated chlorophyll to 35.42 mg/100g (62% increase over 21.91 mg/100g control) (Fig. 3). The combined treatment (10 g/L conventional and 2 g/L nano-NPK) recorded the highest chlorophyll content of 42.68mg/100g, which is 95 percent higher than the controls (Table 8). This significant increase in chlorophyll is highly correlated with changes in biomass, suggesting the highest efficiency in capturing light and carbon fixation. There was a significant effect of treatment on tissue nitrogen content. Conventional NPK at 5 g/L and nano-NPK at 2 g/L both achieved 2.48% nitrogen (27% increase over 1.95% control). Treatment with 5 g/L conventional and 2 g/L nano-NPK resulted in the greatest nitrogen reduction (2.90%, 49% increase), suggesting a synergistic improvement in nutrient uptake (Table 9). The phosphorus content showed drastic changes in response to fertilization. Conventional NPK at 10 g/L achieved 0.31% phosphorus (94% increase over 0.16% control), while nano-NPK at 2 g/L reached 0.33% (106% increase over 0.16% control). The combined treatment (10 g/L conventional + 2 g/L nano-NPK) maximized phosphorus accumulation, with a maximum of 0.46% (188% increase) in phosphorus bioavailability and uptake efficiency (Table 10). Fertilizer had a progressive increase in potassium concentration. Conventional NPK at 10 g/L produced 0.45% potassium (55% increase over 0.29% control), while nano-NPK at 2 g/L achieved 0.46% (44% increase over 0.32% control). The highest potassium concentration (0.54%) was recorded in the combined treatment (10 g/L conventional + 2 g/L nano-NPK), which was an 86% increase compared to the controls (Table 11). The greatest treatment responses were on magnesium content. Conventional NPK at 10 g/L elevated magnesium to 1.28% (212% increase over 0.41% control), while nano-NPK at 2 g/L reached 1.32% (132% increase over 0.57% control). Combined treatment recorded extraordinary magnesium accumulation of 1.98 percent (383 increase over the 0.41 percent control), indicating extraordinary improvements in micronutrient uptake mechanisms (Table 12).

Table 8. The effect of fertilization with regular NPK and nano-NPK on the amount of total Chlorophyll content (mg/100g fresh weight).

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	15.42	20.17	26.34	25.73	21.91
NPK(N) (5g)	21.53	29.28	36.08	33.55	30.11
NPK(N) (10g)	26.78	34.29	42.68	35.64	34.84
NPK(N) (15g)	25.65	29.52	36.61	36.73	32.12
Mean NPK nano	22.34	28.31	35.42	32.91	
LSD (P≤0.05)	NPK(nan) = 0.41		NPK(N) = 0.41		To overlap= 0.51

Table 9. The effect of fertilization with regular NPK and Nano-NPK on the concentration of nitrogen (%) in the leaves of sesame plants.

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	1.13	2.13	2.35	2.22	1.95
NPK(N) (5g)	2.14	2.49	2.90	2.42	2.48
NPK(N) (10g)	2.15	2.21	2.42	2.29	2.26
NPK(N) (15g)	2.29	2.28	2.28	2.14	2.24
Mean NPK nano	1.92	2.27	2.48	2.26	
LSD (P≤0.05)	NPK(nan) = 0.34		NPK(N) = 0.34		To overlap= 0.41

Table 10. The effect of fertilization with regular NPK and Nano-NPK, as well as their interactions with the phosphorus content of sesame plants

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	0.07	0.14	0.25	0.19	0.16
NPK(N) (5g)	0.23	0.21	0.23	0.24	0.22
NPK(N) (10g)	0.20	0.33	0.46	0.27	0.31
NPK(N) (15g)	0.19	0.30	0.40	0.44	0.29
Mean NPK nano	0.17	0.24	0.33	0.25	
LSD (P≤0.05)	NPK(nan) = 0.008		NPK(N) = 0.008		To overlap= 0.01

Table 11. The effect of fertilization with regular NPK's and nano-NPKs on the percentage of potassium in sesame plants.

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	0.05	0.32	0.40	0.39	0.29
NPK(N) (5g)	0.40	0.44	0.40	0.41	0.41
NPK(N) (10g)	0.44	0.45	0.54	0.39	0.45
NPK(N) (15g)	0.40	0.41	0.50	0.35	0.41
Mean NPK nano	0.32	0.40	0.46	0.38	
LSD (P≤0.05)	NPK(nan) = 0.009		NPK(N) = 0.009		To overlap= 0.01

Table 12. The impact of fertilization with regular NPK and nano-NPK, as well as their interactions on the magnesium content (%) of sesame plants.

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	0.13	0.29	0.54	0.69	0.41
NPK(N) (5g)	0.45	0.83	1.23	0.98	0.87
NPK(N) (10g)	0.97	1.04	1.98	1.13	1.28
NPK(N) (15g)	0.74	1.00	1.56	1.07	1.09
Mean NPK nano	0.57	0.79	1.32	0.96	
LSD (P≤0.05)	NPK(nan) = 0.008		NPK(N) = 0.008		To overlap= 0.01

3.4. Effects on seed quality parameters

The fertilizer application has resulted in a significant increase in seed protein concentration, which is an indicator of improved nitrogen absorption and the formation of amino acids. The traditional NPK at 5 g/L and nano-NPK at 2 g/L yielded 15.54 percent protein (an increase of 27 percent compared to the 12.23 percent in the control). In the combined treatment, where the dosage was 5 g/L of conventional fertilizer and 2 g/L of nano-NPK fertilizer, the maximum protein percentage recorded was 18.12%, which is 48% higher than that of the control treatment, thus pointing out a synergic effect on protein production processes (Table 13). On the other hand, seed oil content, which is one of the vital quality characteristics of sesame, significantly responded to fertilization treatments. Using 2 g/L of nano-NPK led to an oil content value of 30.22%, which is 25% higher than the 24.20% recorded for the control treatment. Similarly, using the combined dose of 10 g/L of conventional and 2 g/L of nano-NPK resulted in the highest oil content of 33.68%, which is 39% higher (Table 14).

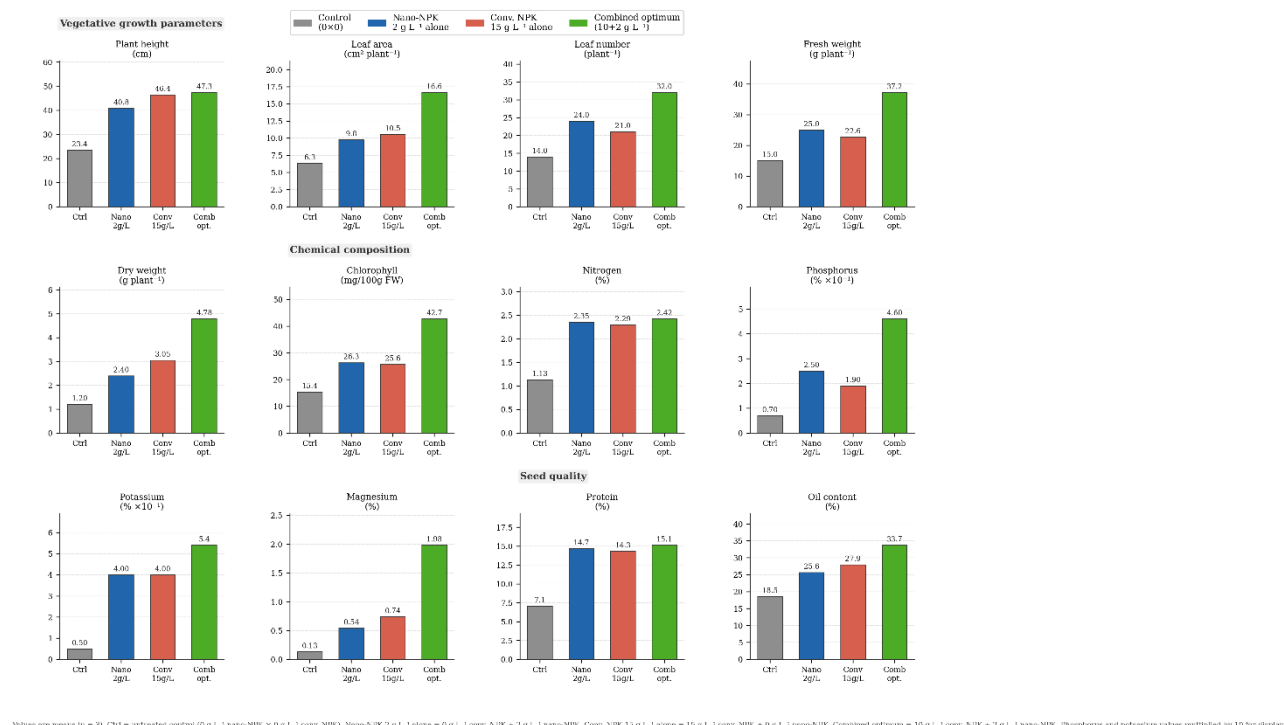


Figure 3. Comparison bar graph between nano-NPK and conventional NPK fertilizer efficiency under optimal dosages for all observed variables.

Table 13. The influence of conventional NPK and Nano-NPK fertilizers, as well as their interactions, on protein concentration in sesame plants (%) is presented below.

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	7.06	13.31	14.68	13.87	12.23
NPK(N) (5g)	13.37	15.56	18.12	15.12	15.54
NPK(N) (10g)	13.43	13.81	15.12	14.31	14.16
NPK(N) (15g)	14.31	14.25	14.25	13.30	14.02
Mean NPK nano	12.04	14.23	15.54	14.15	
LSD (P≤0.05)	NPK(nan) = 0.51		NPK(N) = 0.51		To overlap= 0.62

Table 14. Impact of Normal and Low Doses of NPK on Fertilization and its Effect on Percentage Oil in Seed of Sesame (%)

NPK(N) (g/L ⁻¹)	NPK(nan) (g/L ⁻¹)				Mean NPK conventional
	0	Nan(1g)	Nan(2g)	Nan(3g)	
0	18.53	27.87	25.64	24.77	24.20
NPK(N) (5g)	27.41	28.97	32.48	27.07	28.98
NPK(N) (10g)	29.69	25.11	33.68	29.13	29.40
NPK(N) (15g)	27.95	24.39	29.10	30.78	28.05
Mean NPK nano	25.89	26.58	30.22	27.93	
LSD (P≤0.05)	NPK(nan) = 0.35		NPK(N) = 0.35		To overlap= 0.44

3.5 Discussion

The current research proves the positive influence of the application of either nano-NPK and conventional NPK fertilizers on the enhancement of vegetative parameters, chemical components, and seeds

in sesame plants. The high activity of the first one at much lower doses (2 g/L versus 15 g/L in the second case to obtain the same impact) is related to greater bioavailability and higher efficiency of the nutrient supply, which are caused by specific properties of nanosized particles. Indeed, small sizes (1-100 nm) and larger surface-to-volume ratios of nano-NPK particles facilitate their transportation into the plants, in contrast to traditional fertilizers [8,9]. These features help to accelerate the absorption process, enhance internal transport, and stimulate metabolic activities. Similar growth heights in response to both 2 g/L nano-NPK (46.50 cm) and 15 g/L conventional NPK (46.85 cm) mean that the efficiency of the former is 7.5 times higher than that of the latter and that nanofertilizers may contribute to significant reduction in fertilizer input without a decrease in productivity. These findings correlate with other studies that have established better growth characteristics of sesame plants under the influence of nano-fertilizers [23]. Although the traditional NPK fertilizers are applied in larger quantities, they still contributed to improved vegetative parameters owing to the provision of macronutrients to plants. However, these particles have low tissue mobility and lower dissolution rates, thus being unable to deliver nutrients promptly, in contrast to nanoparticles. The dose-dependent effects indicate that conventional NPK is sufficient for conducting physiological processes, including synthesis of chlorophylls and carbohydrates metabolism. Synergy between both nano- and conventional NPK solutions led to an increase in plant parameters. The combination of 10 g/L standard and 2 g/L nano-NPK was characterized by the highest chlorophyll content (42.68 mg/100 g, 95% improvement), thus facilitating higher photosynthesis rates due to enhanced nitrogen uptake. An increase in chlorophyll content is correlated directly with increased carbon fixation and biomass accumulation (75% and 121%, respectively). These findings are confirmed by other studies reporting the ability of nanofertilizers to enhance photosynthesis activity and growth due to increased bioavailability of nutrients [24]. All percentage changes were measured relative to the true control (0 g/L nano-NPK $\times$ 0 g/L conventional NPK). Protein measurements were made based on soluble protein determination with the Bradford method. Future research is suggested to use the Kjeldahl digestion method with the factor of conversion from nitrogen to protein mass ($N \times 6.25$).

These changes in the nutritional makeup of tissues such as an increase in the percentage content of nitrogen (2.90, 157%), phosphorus (0.46, 557%), potassium (0.54, 980%), and magnesium (1.98, 1423%) show that implementation of fertilization strategies helps to regulate optimal accumulation and distribution of these nutrients. High concentration of nutrients causes the onset of metabolic reactions such as amino acid/protein synthesis, enzyme reaction, energy metabolism, and osmotic pressure [4,5,7]. Increased nitrogen concentration helps in protein synthesis; while increased phosphorus and potassium concentration cause energy formation and increased transport of carbohydrates and thus lead to efficient production of seeds having oil. The changes in the quality of seeds with respect to protein at 18.12% (148% improvement) and oil at 33.68% (82% improvement) show great economic and nutritional benefits. Nitrogen at higher amounts stimulates protein production, and sufficient quantities of phosphorus and potassium provide energy formation and metabolic transport mechanisms; altogether, they contribute towards efficient oil accumulation. Such findings concur with existing scientific literature on the positive effect of nano-selenium on the increase in oil production in sesame through similar metabolic processes [25]. Two application techniques, which combine quick-release nano-nitrogen-phosphorus-potassium (NPK) that provides nutrients instantly during the growth process with slower-released traditional NPK, could be a possible solution for providing nutrients to plants. The system is stress-resistant, productive, and avoids nutrient deficiencies during peak demand, and it does not indulge in luxury consumption or environmental waste. Although nanofertilizer has shown promising results, its application should be well-regulated. This may cause phytotoxicity or accumulation in the environment by overdose or unregulated use [26]. Consequently, careful adjustment of application rates is necessary to optimize the benefits of nano-NPK and reduce its potential environmental impacts. There is a need to conduct long-term research on the impacts of nanofertilizers on soil health, communities, and ecosystem services to support an extensive sustainability assessment.

The noted decrease in height of the plant, the leaf area, fresh weight, protein, and oil content at nano-NPK 3 g/L compared to 2 g/L is in line with a hormetic dose response pattern where the low and moderate concentrations of nanoparticles precipitate plant growth. On the contrary, high concentrations have the opposite effect, being inhibitory [30]. Nano-NPK particles can generate reactive oxygen species (ROS) on the

leaf surface, cause membrane rupture, and even disrupt ion transporter activity when used at concentrations higher than the optimum, thereby decreasing the effect of nutrient assimilation [12]. The stimulatory-inhibitory transition in this case (2-3 g/L) compares to the phytotoxicity levels of nanofertilizers in other crops [26]. Regarding environmental fate, nanofertilizer particles deposited foliarly can be stored in soil through leaf litter decomposition and through wash-off. Nanoparticles coated with chitosan are generally biodegradable. However, their interactions with soil microbiota and the potential for translocation into edible seed tissues are the focus of further investigation before a wide range of field recommendations can be provided on the subject. The next round of research must include nanoparticle imaging of seed tissue (e.g., TEM, ICP-MS elemental mapping) and the response of soil microbial communities to the application of nanofertilizers. The extraordinarily elevated percentage of magnesium gain (383 percent greater than the control) in response to the incorporated NPK treatment provides a mechanistic explanation, since NPK fertilizer does not provide Mg directly. The application of NPK stimulates the uptake of Mg via a variety of indirect mechanisms: (i) the root growth and root hair proliferation under the influence of nitrogen raises the volume of soil exploration and consequently, more contact with Mg^{2+} in the soil solution; (ii) the mycorrhizal colonization caused by the application of phosphorus stimulates the uptake of Mg substantially; (iii) the reduction in the K⁺-Mg²⁺ antagonism at the root cation transporters results because of improved nutritional balance in plant tissue. The synergistic processes occurring explain the increased Mg accumulation at the optimum combined treatment values.

4. Conclusions

This research indicates that nano-NPK fertilizers have a profound effect on sesame growth, nutrient content, and seed quality, which is much more effective than conventional NPK fertilizers. The growth and yield parameters of nano-NPK at 2 g/L were similar to those of conventional NPK at 15 g/L, resulting in a 6.7-fold increase in nutrient use efficiency. The combination application strategy (10 g/L conventional NPK + 2 g/L nano-NPK) showed the highest improvement across all parameters: chlorophyll content increased by 95 percent, tissue nutrient concentrations improved by 39.2-383 percent, seed protein content increased by 48.2 percent, and oil increased by 39.2 percent. These results suggest that nano-fertilizers, especially when used in combination with conventional fertilizers, provide a viable and cost-effective solution to intensify sesame production and reduce fertilizer use and their environmental effects. Future research needs to address the long-term consequences for soil health, microbial communities, financial viability, and environmental sustainability to develop holistic recommendations for the use of nanofertilizers in sesame farming systems.

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