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Full Length Article

Effect of Nitrogen and Phosphorus Application Rate on Growth and Yield of Groundnut (*Arachis hypogaea*) on the Coastal Sandy Soil

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Abstract

Groundnut is a vital oilseed and cash crop in Vietnam, particularly in Nghe An province, where it is extensively cultivated on nutrient-poor coastal sandy soils. However, the productivity of groundnut in these areas is limited due to unbalanced fertilization practices. To address nutrient limitations in this challenging environment, this study evaluated the effects of six fertilization treatments formed by combining three nitrogen (N) application rates (20, 40 and 60 kg. ha^{-1}) with two phosphorus (P_2O_5) rates (60 and 90 kg. ha^{-1}). Accordingly, six treatment combinations were established in a factorial arrangement: T1 (N20P60), T2 (N20P90), T3 (N40P60), T4 (N40P90), T5 (N60P60) and T6 (N60P90), with T1 serving as the control treatment based on local farmer practices. All experimental plots received the same base fertilization: 10 tons ha^{-1} of manure, 60 kg. ha^{-1} of K_2O and 800 kg. ha^{-1} of lime. The results showed that N and P fertilization significantly influenced growth, reproductive development, and yield components. The treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} produced the highest plant height (37.2 cm), leaf number (32.7 leaves $plant^{-1}$), flower production (74 flowers $plant^{-1}$) and biomass accumulation. It also led to the highest pod number (22.4), 100-pod weight (114.4 g), 100-seed weight (51.3 g), shelling percentage (64%), seed protein content (31.10%), and actual yield (3.31 tons ha^{-1}). In terms of economic performance, the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} recorded the highest net return (1702.75 USD ha^{-1}) and value-cost ratio (VCR = 2.58), outperforming both lower and higher fertilizer rates. These findings highlight the agronomic and economic advantage of balanced nutrient management, particularly the combination of 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}, as an optimal strategy for sustainable groundnut production on coastal sandy soils in central Vietnam.

Keywords: Soil fertility management; Legume crops; Fertilizer optimization; Sandy land agriculture; Protein content

Introduction

Groundnut (*Arachis hypogaea* L.) is a leguminous crop native to Latin America and is widely cultivated across the intertropical belt, particularly in arid and semi-arid regions (Bekele *et al*. 2022). It serves as a vital oilseed and cash crop both globally and in Vietnam (Hoa *et al*. 2022). According to FAO (2023), Vietnam ranks 25th in productivity and 17th in total groundnut production worldwide. The country's groundnut cultivation area accounts for approximately 0.50–0.67% of the global total, while its production contributes 0.79–0.95% of global output. Notably, the average groundnut yield in Vietnam (0.71–0.83 tons ha^{-1}) is generally higher than the global average (GSO 2023).

Nghe An, a province located in the North Central Coast of Vietnam, has demonstrated significantly higher economic efficiency from groundnut cultivation compared to other short-term food and industrial crops. The province accounts for nearly one-quarter of Vietnam's total groundnut cultivation area and leads the country in kernel production. Each year, approximately 17,500–18,000 ha of groundnut are planted, producing around 40,000 tons of in-shell groundnut. Of this, roughly 28,000 tons can be exported, equivalent to approximately 19,000 tons of groundnut kernels, supplying 50–60% of the nation's total groundnut exports (NASO 2023).

In Nghe An, groundnuts are primarily cultivated on alluvial soils, infertile grey soils, and coastal sandy soils, the latter of which accounts for about 60% of the total groundnut cultivation area (NASO 2023). However, groundnut productivity on coastal sandy soils remains low due to poor fertility and unbalanced fertilizer practices. Although previous studies have been conducted on fertilizer use for groundnut in Vietnam—mainly in the south-central coastal provinces such as Khanh Hoa, Binh Dinh and Phu Yen (Do *et al*. 2021; Hoa *et al*. 2022)—their findings may not be directly

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applicable to the unique soil and climatic conditions of Nghe An. In this region, fertilizer application often depends on farmers' financial capacity, resulting in unbalanced and inadequate nutrient supply. Furthermore, fertilizer recommendations rarely account for local soil characteristics, ecological zones, and specific cultivation conditions.

Nitrogen (N) is an essential nutrient that plays a critical role in achieving high yields, as it is a key component of amino acids and proteins (Anas *et al*. 2020). While N application is necessary, especially in arid regions, excessive use can lead to environmental degradation and reduced soil health (Paramasivan *et al*. 2023). Moreover, high N levels can disrupt N metabolism, reducing seed protein quality (Zhang *et al*. 2008).

Soil phosphorus (P) concentrations are often high; however, their biological effects on plants are complex, influencing key physiological processes in groundnut, including N fixation. Elevated P levels can affect nodule development, N uptake, and overall plant metabolism—processes that are essential for enhancing groundnut yield (Brar and Manhas 2023; Kamal *et al*. 2024). P fertilizers play a critical role by promoting root development, improving nutrient and water use efficiency, and ultimately increasing yield (Sunitha *et al*. 2023; Kamal *et al*. 2024).

Integrated nutrient management practices that combine N and P have been shown to significantly enhance groundnut growth parameters and yield (Paramasivan *et al*. 2023). Fertilizers are crucial for regulating plant growth and development, contributing substantially to crop productivity (Naab *et al*. 2009). However, these benefits can only be fully realized when fertilizers are applied in a balanced and rational manner. Improper or excessive use may lead to environmental degradation or suboptimal crop performance (Tiwari 2001; Songsri *et al*. 2008). Previous studies have emphasized that successful integrated nutrient management depends on carefully calibrated and site-specific fertilization strategies (Wu and Ma 2015; Kushwah *et al*. 2023).

Despite the recognized roles of N and P in groundnut development, there is limited research on their optimal application rates for coastal sandy soils in Nghe An Province. Understanding these nutrient requirements is essential to formulate effective fertilization strategies that can enhance productivity and sustainability in this region. Therefore, the objective of this study was to evaluate the effects of N and P fertilization on the growth performance and yield of groundnut cultivated on coastal sandy soils in Nghe An, and to determine the most effective nutrient application rates for improving crop productivity.

Materials and Methods

Experimental details and treatments

Experimental material: The experiment was conducted at the farm of the School of Agriculture and Natural Resources, Vinh University, Dien Chau District, Nghe An Province, Vietnam, during the spring crop of 2024 (from February to June). During the experiment, the average temperature and humidity were 23.36°C and 81.6%, respectively (Table 1). In this study, the soil properties of the experimental site are described in detail in Table 2, which shows neutral pH and low organic carbon content. The groundnut variety L14, recognized as a technically advanced variety by Decision No. 5310 QD/BNN-KHCN, dated November 29, 2002, was used for this research.

Treatments and experimental details: This study evaluated the effects of six fertilization treatments formed by combining three nitrogen (N) application rates (20, 40 and 60 kg. ha^{-1}) with two phosphorus (P_2O_5) rates (60 and 90 kg. ha^{-1}). Accordingly, six treatment combinations were established in a factorial arrangement: T1 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}), T2 (20 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}), T3 (40 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}), T4 (40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}), T5 (60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}) and T6 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}), with T1 serving as the control treatment based on local farmer practices. All experimental plots received the same base fertilization: 10 tons ha^{-1} of manure, 60 kg. ha^{-1} of K_2O, and 800 kg. ha^{-1} of lime. The experiment was designed as randomized complete block design (RCBD) with three replications and each experimental plot covered an area of 15 m^2 (3 m × 5 m). Before sowing, the soil was thoroughly plowed and harrowed, leveled, and cleared of weeds. Soil moisture at the time of sowing was maintained at approximately 75–80% of the field's maximum water-holding capacity. Groundnut seeds were manually sown at a spacing of 25 cm between rows and 10 cm between plants, equivalent to a planting density of 31 plants m^{-2}. Irrigation was applied by filling furrows to two-thirds of the ridge height, allowing the water to soak evenly before draining. All field management practices followed the National Technical Regulation QCVN 01-57:2011/BNNPTNT issued by the Department of Crop Production, Ministry of Agriculture and Rural Development (MARD 2011).

Data collection

Plant height was measured from the first branching point to the apex of the main stem on ten randomly selected plants per plot at three critical growth stages: flowering, full bloom, and harvest. Leaf count plant^{-1} was tracked during the same stages. The number of flowers plant^{-1} was observed daily until the daily count dropped below one and did not increase continuously for three consecutive days.
The effective flower rate was calculated using the formula:

$$\text{Effective flower ratio (\%)} = \frac{\text{Number of filled pods plant}^{-1}}{\text{Total number of flowers plant}^{-1}} \times 100$$

Fresh and dry nodule weight: Root samples were cleaned and separated for analysis. The fresh weight of root nodules was recorded, and the dry weight was measured after drying at 105°C until constant weight was achieved. Protein content was analyzed using the Kjeldahl method, following the official procedure outlined by AOAC (2005).

Table 1: Temperature, rainfall and humidity variations during the experiment

Month	Temperature (°C)			Rainfall (mm)		Humidity (%)		Sunshine duration (h)
	Mean	Max	Min	Number of rainy days	Mean	Mean	Min	
Feb	17.7	21.5	13.1	13	10.7	88	77	86
Mar	16.9	20.8	11.0	22	15.5	87	77	50
Apr	23	27.0	18.5	8	34.2	86	78	107
May	27.5	31.5	23.0	11	95.0	80	64	227
Jun	31.7	40	23.6	12	104.8	67	38	206

Source: National Center for Hydro-Meteorological Forecasting (NCHMF), Vietnam

Table 2: Basic soil properties of the experimental location

Determination		Unit	Value	Rating
pH (H_2O)		-	7.2	Neutral
pH (KCl)		-	6.3	Neutral
Organic carbon		%	0.52	Low
Total nitrogen		%	0.06	Low
Total phosphorus		%	0.1	Medium
Total potassium		%	0.22	Low
Available phosphorus		mg/100 g soil	5.5	Medium
Available potassium		mg/100 g soil	3.76	Low
Exchangeable base	Ca^{2+}	meq/100 g soil	2.24	Low
	Mg^{2+}	meq/100 g soil	0.31	Very low
	K^+	meq/100 g soil	0.08	Very low
	Na^+	meq/100 g soil	0.08	Very low
Sand		%	76.8	
Silt		%	11.6	
Clay		%	11.6	

Matter weight: Ten plants per plot were uprooted at each monitoring stage. The fresh weight was recorded, and the plants were then dried to a constant weight to determine their final dry weight.

The pod number and filled pods were counted on ten sample plants per plot and the averages were calculated for both parameters.

Weight of 100 pod and 100 seed: A random sample of 100 pod and 100 seed, with approximately 12% moisture content, was taken, and their weights were recorded.

Shelling percent was calculated using the formula:

$$\text{Shelling percent (\%)} = \frac{\text{Weight of all seeds from random sample}}{\text{Weight of 100 randomly selected pods}} \times 100$$

Theoretical yield was estimated based on the number of plants m^{-2}, the number of filled pods $plant^{-1}$ and 100 pods weight. The formula used for calculating theoretical yield (tons ha^{-1}) was as follows:

$$\text{Theoretical yield} = \frac{\text{Number of plants m}^{-2} \times \text{Number of filled pods plant}^{-1} \times \text{Weight of 100 pods} \times 7500\ \text{m}^2}{10^8}$$

Actual yield: Pods were harvested separately from each plot, with only well-filled and mature pods selected. After sun-drying to approximately 12% seed moisture content, the total pod weight per plot was recorded.

$$\text{Actual yield} = \frac{\text{Dry pod weight per experimental plot} \times 7500}{15 \times 10^3}\ (\text{tons ha}^{-1}).$$

Statistical analysis

The experiment followed a factorial arrangement of treatments in a randomized complete block design (RCBD), involving two factors: nitrogen (three levels: 20, 40 and 60 kg. ha^{-1}) and phosphorus (two levels: 60 and 90 kg. ha^{-1}), resulting in six treatment combinations. Each treatment was replicated three times. The collected data were subjected to two-way analysis of variance (ANOVA) to assess the main effects of nitrogen and phosphorus, as well as their interaction. Mean separation was conducted using the Least Significant Difference (LSD) test at a 5% significance level ($P < 0.05$). Data normality was verified before ANOVA to ensure statistical validity. All statistical analyses were performed using IRRISTAT software.

Results

Growth parameters

Nitrogen (N) and phosphorus (P) application significantly influenced groundnut growth at all stages (Table 3). Plant height increased progressively with higher N and P levels. At flowering, plant height ranged from 10.4 cm (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}) to 11.6 cm (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}) and reached 38.2 cm at harvest in the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. Similarly, leaf number followed this pattern, increasing from 18.0 leaves $plant^{-1}$ (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}) to 21.9 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}). The treatment of 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} consistently showed superior plant height and foliage development, reflecting synergistic effects of high N and P.

Flowering characteristics were notably influenced. The total number of flowers increased with higher N, with the maximum (78.7 flowers $plant^{-1}$) in the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. Effective flowers were highest in the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} (21.02%) and lowest in the treatment 60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} (18.59%), suggesting excessive N can reduce reproductive efficiency if not supported by sufficient P. Flowering duration ranged from 23 to 27 days, with longer durations under higher N and P levels.

Nodule development was significantly affected by treatments (Table 4). At full bloom, fresh nodule weight was highest in the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} (0.59 g $plant^{-1}$), while the lowest was in the treatment 20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} (0.52 g $plant^{-1}$). Nodule dry weights followed a similar trend. At harvest, the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} maintained the highest values (2.11 g fresh, 0.210 g dry), showing that balanced fertilization enhances root symbiosis. Excessive N without adequate P (60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} and 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}) led to decreased nodule biomass at harvest.

Table 3: Effects of nitrogen and phosphorus on growth parameters and flowering characteristics of groundnut

Treatments	Plant height (cm)			Leaf number			Flowering characteristics		
	Flowering	Full bloom	Harvesting	Flowering	Full bloom	Harvesting	Total flowers plant^{-1}	Effective flowers (%)	Flowering duration (days)
T1 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	10.4^{d}	17.1^{c}	36.0^{d}	21.6^{c}	30.1^{c}	18.0^{d}	72.5^{c}	19.94^{c}	23
T2 (20 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	10.7^{cd}	17.5^{bc}	36.3^{d}	21.7^{c}	30.2^{c}	18.6^{c}	73.3^{bc}	19.85^{c}	24
T3 (40 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	10.8^{bcd}	17.4^{bc}	36.7^{c}	22.1^{c}	30.8^{c}	18.7^{c}	73.5^{abc}	19.97^{c}	24
T4 (40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	10.9^{bc}	18.0^{ab}	37.2^{b}	24^{ab}	32.7^{b}	20.2^{b}	74^{ab}	21.02^{ab}	24
T5 (60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	11.2^{ab}	17.7^{bc}	37.4^{b}	23.7^{b}	32.1^{b}	19.8^{b}	73.9^{ab}	18.59^{bc}	24
T6 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	11.6^{a}	18.7^{a}	38.2a	24.6^{a}	34.3^{a}	21.9^{a}	78.7^{a}	19.58^{a}	27
$LSD_{0.05}$	0.49	0.80	0.47	0.78	0.84	0.36	1.0	0.5	-

N = Nitrogen; P_2O_5 = Phosphorus pentoxide; LSD = Least significant difference at 5% level. Statistically significant differences are shown by different superscript letters in the same column ($P < 0.05$)

Table 4: Effect of nitrogen and phosphorus application rate on nodule development and biomass of groundnut

Treatments	Nodule fresh weight (g plant^{-1})			Nodule dry weight (g plant^{-1})			Fresh matter weight (g plant^{-1})			Dry matter weight (g plant^{-1})		
	Flowering	Full bloom	Harvesting	Flowering	Full bloom	Harvesting	Flowering	Full bloom	Harvesting	Flowering	Full bloom	Harvesting
T1 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	0.21^{c}	0.52^{c}	1.94^{b}	0.020^{d}	0.051^{b}	0.196^{b}	18.3^{d}	33.1^{c}	135.8^{c}	3.4^{b}	5.8^{d}	38.1^{d}
T2 (20 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	0.22^{b}	0.53^{c}	1.96^{b}	0.023c	0.053^{b}	0.197^{b}	18.4^{d}	33.4^{d}	136.2^{c}	3.5^{b}	6.0^{c}	38.4^{d}
T3 (40 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	0.23^{b}	0.54^{bc}	1.98^{b}	0.022cd	0.055^{a}	0.200^{b}	18.7^{cd}	33.5^{cd}	136.4^{c}	3.5^{b}	6.2^{c}	38.5^{cd}
T4 (40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	0.28^{a}	0.59^{a}	2.11^{a}	0.029a	0.060^{a}	0.210^{a}	19.5^{b}	34.1^{b}	138.5^{b}	3.6^{b}	6.8^{ab}	40.1^{b}
T5 (60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	0.24^{b}	0.56^{b}	1.16^{c}	0.025b	0.055^{a}	0.130^{c}	19.2^{b}	33.8^{bc}	137.3^{bc}	4.2^{b}	6.5^{b}	39.7^{bc}
T6 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	0.28^{a}	0.52^{c}	1.17^{c}	0.029a	0.052^{b}	0.140c	20.2^{a}	34.5^{a}	140.7^{a}	4.82^{a}	6.94^{a}	42.9^{a}
$LSD_{0.05}$	0.018	0.022	0.045	0.0018	0.0016	0.0048	0.42	0.3	1.5	0.3	0.15	1.6

N = Nitrogen; P_2O_5 = Phosphorus pentoxide; LSD = Least significant difference at 5% level. Statistically significant differences are shown by different superscript letters in the same column ($P < 0.05$)

Table 5: Effect of nitrogen and phosphorus application rate on yield components and yield of groundnut

Treatments	Number of pods plant^{-1}	Number of filled pods plant^{-1}	100 pods weight (g)	100 seeds weight (g)	Theoretical yield (tons ha^{-1})	Actual yield (tons ha^{-1})
T1 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	20.7^{d}	14.4^{c}	106.6^{e}	49.7^{d}	3.81^{e}	2.857^{e}
T2 (20 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	21^{cd}	14.6^{c}	110.6^{c}	50.3^{bc}	3.99^{d}	2.972^{d}
T3 (40 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	21.2^{cd}	14.7^{bc}	109.1^{d}	49.9^{cd}	3.96^{d}	2.971^{d}
T4 (40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	22.4^{b}	15.6^{a}	114.4^{b}	51.3^{a}	4.41^{a}	3.305^{a}
T5 (60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	21.6^{c}	15.2^{ab}	113.6^{b}	50.9^{ab}	4.28^{c}	3.01^{c}
T6 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	24.1^{a}	15.1^{b}	115.7^{a}	50.4^{a}	4.34^{ab}	3.261^{ab}
$LSD_{0.05}$	0.64	0.43	1.47	0.47	0.84	0.64

N = Nitrogen; P_2O_5 = Phosphorus pentoxide; LSD = Least significant difference at 5% level. Statistically significant differences are shown by different superscript letters in the same column ($P < 0.05$)

Biomass accumulation increased with fertilizer application (Table 4). The treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} achieved the highest fresh matter (140.7 g plant^{-1}) and dry matter weight (42.9 g plant^{-1}) at harvest. Both parameters increased significantly with higher P rates, especially when N was ≥ 40 kg. ha^{-1}. These results indicate that biomass production benefits from synergistic N–P interaction, particularly under coastal sandy soil conditions.

Yield and yield components

Yield components were markedly improved by N and P application (Table 5). The number of pods plant^{-1} increased from 20.7 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}) to 24.1 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}), while filled pods rose from 14.4 to 15.6 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} to 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}). Notably, the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} produced the highest yield components with optimal N–P balance, while the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} showed minimal gains despite the highest N level.

The 100 pod weight increased with both N and P, reaching 115.7 g in the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. The 100 seed weight also improved significantly, peaking at 51.3 g in the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. These results suggest that excessive N may not further enhance seed development beyond the moderate application level.

Theoretical yield ranged from 3.81 tons ha^{-1} (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}) to 4.41 tons ha^{-1} (40 kg N ha^{-1} + 90

Table 6: Effect of nitrogen and phosphorus application rate on grain quality of groundnut

Treatments	Shelling percent (%)	Protein content (%)
T1 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	63.90^{bc}	29.71^{d}
T2 (20 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	63.60^{c}	29.95^{cd}
T3 (40 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	63.80^{bc}	30.66^{bc}
T4 (40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	64.00^{b}	31.10^{ab}
T5 (60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	63.70^{bc}	30.91^{b}
T6 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	64.80^{a}	31.46^{a}
$LSD_{0.05}$	0.31	0.62

N = Nitrogen; P_2O_5 = Phosphorus pentoxide; LSD = Least significant difference at 5% level. Statistically significant differences are shown by different superscript letters in the same column ($P < 0.05$)

Table 7: Economic efficiency of nitrogen and phosphorus fertilization in groundnut production

Treatment	Actual yield (tons ha^{-1})	Gross return (USD ha^{-1})	Total cost (USD ha^{-1})	Net return (USD ha^{-1})	VCR
T1 (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	2.86	2406.05	1030.98	1375.07	2.33
T2 (20 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	2.97	2502.02	1059.68	1442.34	2.36
T3 (40 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	2.97	2501.18	1050.91	1450.26	2.38
T4 (40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	3.31	2782.36	1079.61	1702.75	2.58
T5 (60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1})	3.01	2534.01	1070.89	1463.12	2.37
T6 (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1})	3.16	2658.18	1094.38	1563.80	2.43

N = Nitrogen; P_2O_5 = Phosphorus pentoxide; Gross return was calculated based on the market price of groundnut yield. VCR (Value Cost Ratio) = Gross return / Total cost

kg P_2O_5 ha^{-1}), while actual yield ranged from 2.857 tons ha^{-1} to 3.305 tons ha^{-1}. The highest actual yield was in the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}, with no significant difference compared to the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. This implies that increasing N beyond 40 kg. ha^{-1} does not translate to proportional yield gains.

Grain quality and economic efficiency

Shelling percentage showed minor variation across treatments, with the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} showing the highest at 64.80% (Table 6). This may reflect better kernel development under higher P and balanced N inputs.

Protein content in seeds increased with higher N and P levels, ranging from 29.71% (20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1}) to 31.46% (60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}). Treatments with 90 kg P_2O_5 ha^{-1} consistently had higher protein content, indicating phosphorus's key role in enhancing quality. However, maximum protein content did not always correspond with maximum yield, again emphasizing that the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} provided the best balance of productivity and quality.

Economic analysis revealed significant differences in profitability and input efficiency among treatments (Table 7). The highest actual yield (3.31 tons ha^{-1}), gross return (2782.36 USD ha^{-1}), and net return (1702.75 USD ha^{-1}) were recorded in the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}, which also had the highest value-cost ratio (VCR = 2.58). The treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} produced a slightly lower yield (3.16 tons ha^{-1}) and a lower VCR (2.43), indicating diminishing economic returns with increased N input. Treatments with lower fertilizer rates, such as the treatment 20 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} and 20 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}, showed reduced yields and profits, despite moderate VCRs (2.33–2.36). The results clearly show that the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} achieved the best balance of productivity and profitability, making it the most economically efficient fertilization strategy for groundnut cultivation on coastal sandy soils.

Discussion

This study demonstrated that N and P application rates significantly influence the growth dynamics, yield components, and seed quality of groundnut cultivated on coastal sandy soils. These soils are characterized by low fertility, poor organic matter, and limited nutrient-holding capacity, which require careful nutrient management (Do *et al.* 2021). In such fragile agro-ecosystems, nutrient availability becomes a decisive factor in determining crop performance. The findings of this study support the hypothesis that balanced and moderate N–P application can enhance physiological performance and productivity more effectively than excessive nutrient input.

Vegetative growth parameters such as plant height and leaf number increased consistently with higher N and P levels, reflecting the combined role of N in promoting cell expansion, photosynthetic area, and overall biomass production, and of P in enhancing root development, nutrient uptake efficiency, and energy metabolism (Idikut *et al*. 2022; Murtaza *et al*. 2022; Liu *et al*. 2023). The treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} produced the highest values for plant height and foliage development, confirming the direct effect of high nutrient supply on vegetative vigor. However, this vigorous vegetative growth did not result in proportionally higher yield, suggesting that beyond a certain threshold, nutrient inputs may shift assimilate allocation toward vegetative structures, thus limiting reproductive potential. This pattern supports the view that excessive nutrient supply may favor vegetative over reproductive growth, reducing resource-use efficiency (Huang *et al*. 2017; Hussein and Benmoussa 2023).

The flowering characteristics revealed a similar trend. Although the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} had the highest total flower number and the longest flowering duration, its effective flower ratio was lower than that of 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}, which achieved a better balance between vegetative growth and reproductive efficiency. This suggests that high N may induce prolonged vegetative and reproductive activity without improving reproductive success. In contrast, the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} maintained a more compact flowering window with higher reproductive efficiency. This observation aligns with previous findings that surplus nitrogen can prolong flowering but reduce reproductive success due to flower abortion and poor pod setting (Yun *et al*. 2023). The synchronization of vegetative and reproductive phases in the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} likely contributed more effective pollination and pod development.

Nodule development exhibited a strong correlation with the applied nutrient regime, particularly the balance between N and P inputs. Among the treatments, the treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} recorded the highest fresh and dry nodule weight, indicating robust biological nitrogen fixation under moderate N and high P conditions. This result suggests that an optimal supply of N does not suppress, but rather complements, the symbiotic association between groundnut roots and rhizobia when balanced with sufficient P. In contrast, excessive N levels in the treatment 60 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} and 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} appeared to suppress nodulation, likely due to a feedback inhibition mechanism in which high concentrations of mineral N in the soil reduce the plant's dependence on symbiotic nitrogen fixation (Ogola *et al*. 2012; Murtaza *et al*. 2022). These findings underscore the sensitivity of the groundnut–rhizobia interaction to nutrient imbalance and the need for carefully balanced fertilization strategies. Moreover, P played a critical role in supporting both nodule biomass and nitrogenase activity, as previously reported by Bekele *et al*. (2019), reinforcing the view that adequate P availability is essential to maintain functional nodulation, especially in sandy soils that are typically low in available P.

Biomass accumulation increased with higher N and P, peaking in the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. However, this did not translate into the highest yield, reinforcing that total biomass does not directly predict reproductive success. Instead, it indicates that while the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} effectively promoted shoot and leaf growth, a large proportion of assimilates remained in vegetative tissues rather than being allocated to pods and seeds. Similar findings have been reported by Tekulu *et al*. (2020) and Mekdad *et al*. (2021), where overly lush vegetative growth limited assimilate partitioning to reproductive organs. The treatment 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} achieved the highest actual yield despite slightly lower biomass, indicating better partitioning efficiency and assimilate redistribution from source to sink tissues. Moreover, yield components such as 100 pod weight and 100 seed weight were significantly improved by N and P, particularly in the treatments 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} and 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. However, the marginal increase in these parameters between the treatments 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} and 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} did not justify the higher N input in the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}, reaffirming the principle of diminishing returns. In the present study, the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} resulted in slightly higher pod and seed weights compared to 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}; however, the differences were not statistically significant. This suggests that beyond a certain threshold—around 40 kg N ha^{-1} in this context—increasing nitrogen does not lead to proportional gains in yield traits. This observation supports the concept that N-use efficiency declines at higher application rates, as excessive N inputs may suppress reproductive development by promoting excessive vegetative growth (Hussein and Benmoussa 2023).

Grain quality, especially protein content, also responded positively to increasing N and P levels. The highest protein content was observed in the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} (31.46%), followed closely by 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} (31.10%), reflecting the role of N in amino acid synthesis and protein accumulation during seed development (Sagvekar *et al*. 2017; Paramasivan *et al*. 2023). However, this marginal gain under 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} did not justify the higher fertilizer cost, especially considering the comparable performance of 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1}. Likewise, shelling percentage increased slightly under higher nutrient rates but without a significant economic advantage. These minor differences in quality traits suggest that beyond a certain input threshold, improvements in nutritional value are minimal and do not translate into greater marketability or profitability (Hasan and Sahid 2016; Kambali and Gundlur 2020).

In terms of economic returns, the combination of 40 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} not only maximized yield and quality but also delivered the highest net profit (1702.75 USD ha^{-1}) and the most favorable value-cost ratio (VCR = 2.58). Although the treatment 60 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} performed similarly in agronomic traits, its higher input cost reduced its net return and VCR (2.43), confirming the diminishing economic returns of high N fertilization. These findings are consistent with Nazir *et al*. (2022), who reported that nutrient application beyond crop requirement reduces profitability, even when yield gains appear marginal. Thus, the integration of yield, quality, and economic analysis strongly supports 40 kg N ha^{-1} + 90 kg P_2O_5 ha^{-1} as the most efficient and sustainable fertilization strategy. This treatment provides a balance between input use and output benefit, which is critical for smallholder farmers operating on marginal coastal sandy soils, where fertilizer efficiency and cost-effectiveness are key to long-term sustainability.

Conclusion

This study demonstrated that the combined application of N and P significantly improved the growth, yield components, and productivity of groundnut cultivated on coastal sandy soils. Among the treatments, the application of 40 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} (T4) consistently produced the highest values for plant height, leaf number, pod number, pod and seed weight, and actual yield. The findings highlight the importance of balanced fertilization in overcoming the limitations of nutrient-poor sandy soils. This fertilization strategy is recommended for groundnut cultivation in Nghe An Province and similar agro-ecological regions to enhance both crop performance and profitability.

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Author Contributions

Minh Xuan Tran: Conceptualization, methodology, formal analysis, initial editing and final draft. Vinh Dinh Nguyen: Experimental design, writing—review and editing. Binh Thi Ta: Data curation, statistical analysis and visualization. Ngan Kim Thi Tran and Mai Thi Hoang: Experimental data and initial draft. Giang Huong Thi Nguyen: Literature review and manuscript preparation.

Conflicts of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available at the corresponding author's fair request.

Ethics Approval

Not applicable to this work.

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