

ENHANCED GROWTH AND YIELD OF CHIA (*SALVIA HISPANICA* L.) THROUGH PHOSPHORUS-INDUCED SOIL PROPERTY IMPROVEMENTS

AKM MOSHAROF HOSSAIN¹, MST. HABIBA AKHTER¹, KAMRUNNAHAR K.V¹, MD. MUKTADIRUL ISLAM², MD. JAHIDUL ISLAM³, MOAZ HOSEN PRAMANIK³, MD. MIJANUR RAHMAN¹, AMENAH S. ALOTAIBI^{4*}, SHEKHA T. ALQAHTANI⁵, HAKKI AKDENIZ⁶, MOHAMED M. I HELAL⁷, ZEKI ERDEN⁸, MURAT ERMAN⁸, ASHRAF M. METWALLY⁹ AND MOHAMMAD SOHIDUL ISLAM^{10*}

¹Department of Soil Science, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh

²Technology Development Officer, Advanta Seeds International, Bangladesh

³Department of Agricultural Chemistry, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh

⁴Department of Biology, Faculty of Science, University of Tabuk, Tabuk 71491, Saudi Arabia

⁵Department of Biology, College of Science, University of Bisha, P.O. Box 551, Bisha 61922, Saudi Arabia

⁶Iğdır University, Department of Agronomy, Faculty of Agriculture, 7600-Iğdır, Turkey

⁷Basic Sciences and Preparatory Year Department, North Private College of Nursing, Arar, KSA

⁸Department of Field Crops, Faculty of Agriculture, Siirt University, Siirt, Turkey

⁹Department of Biological Sciences, College of Science, King Faisal University, Al-Ahsa, 31982, Saudi Arabia

¹⁰Department of Agronomy, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh

*Corresponding author's email: a_alotaibi@ut.edu.sa; islam.agn@hstu.ac.bd

Abstract

A field experiment was conducted from November 2022 to February 2023 at Boda Upazila, Panchagarh District, located in Agroecological Zone 1 (AEZ-1) of Bangladesh. The objective was to examine the effects of different phosphorus (P) levels on the growth and yield of chia plants (*Salvia hispanica*). The trial included six levels of phosphorus, designated as T₀ (0 kg ha⁻¹), T₁ (20 kg ha⁻¹), T₂ (40 kg ha⁻¹), T₃ (60 kg ha⁻¹), T₄ (80 kg ha⁻¹), and T₅ (100 kg ha⁻¹), using Triple Superphosphate (TSP) as the phosphorus source. The treatments were organized in a Randomized Complete Block Design (RCBD) with four replications. Results revealed that P significantly affected the morphology and growth characteristics of chia, contributing to an increase in yields, as well as improving the soil properties. However, the application of P at 60 kg ha⁻¹ (T₃) resulted in the highest values for morphological and growth attributes. Specifically, the morphological traits such as plant height (105.24 cm), leaf number plant⁻¹ (54.25), number of branches plant⁻¹ (30.50), growth traits like fresh and dry weights (3.18 and 2.52 t ha⁻¹, respectively), and yield contributing characteristics such as number of inflorescences plant⁻¹ (24.63), length of inflorescences (13.60 cm), number of seeds inflorescence⁻¹ (522.30), and 1000-seed weight (1.27 g). Moreover, P fertilization @ 60 kg ha⁻¹ showed the highest yield indices like seed yield (0.44 t ha⁻¹), stover yield (2.03 t ha⁻¹), and biological yield (2.47 t ha⁻¹). The values obtained for the majority of the measured indices were statistically comparable between T₃ and T₄ treatments. Conversely, the control treatment (T₀) resulted in the lowest values for growth and yield parameters. Moreover, phosphorus fertilization significantly enhanced soil phosphorus, potassium, and sulfur contents, improving the nutrient availability for plants. The levels of phosphorus and sulfur gradually increased with higher phosphorus application rates, while potassium levels increased up to the application rate of 80 kg ha⁻¹. Therefore, the application of phosphorus at the rate of 60 kg ha⁻¹ is the most suitable dose for better growth and yield of chia in the AEZ-1 area of Bangladesh.

Key words: Phosphorus; Growth; Yield; Soil properties; Chia

Introduction

Chia (*Salvia hispanica* L.) is an annual oilseed crop belonging to the Lamiaceae family, and has its origins in Mexico and Guatemala (Ixtaina *et al.*, 2008). Chia is recognized for its exceptional nutritional profile, chia has emerged as a superfood, offering a potential solution to combat malnutrition globally. Chia seeds are highly valued for their nutritional properties and medicinal benefits, containing significant levels of protein (15-25%), fats (30-33%), carbohydrates (26-41%), dietary fiber (18-30%), and ash (4-5%). The moisture content of the seeds ranges from 6% to 8% (Ixtaina *et al.*, 2010; Jiménez *et al.*, 2013). They are also rich in vitamins,

minerals, antioxidants, and polyphenols (Ixtaina *et al.*, 2008). Additionally, chia seeds contain high levels of B vitamins, calcium, phosphorus, and potassium (Muñoz *et al.*, 2012, 2013). Chia seeds have the potential to reduce the risk of chronic degenerative diseases (Da Rosa *et al.*, 2017). The lipid content in chia seeds ranges from 25% to 40%, with 60% of the total lipids being alpha-linolenic acid (ALA, omega-3) and 20% being linoleic acid (omega-6) (Bresson *et al.*, 2009). Following the extraction of oil from chia seeds, the residual material contains significant amounts of dietary fiber (33.9 g per 100 g) and protein (17 g per 100 g) (Ayerza and Coates, 2002). The nutritional and therapeutic benefits of chia are currently under extensive research by many

scientific institutions, highlighting its significant role in human health and nutrition.

The chia plant is primarily cultivated for its seed production and nutrient-rich leaves (Bilalis *et al.*, 2016). Chia seeds contain abundant vitamins, minerals, proteins, antioxidants, and polyunsaturated fatty acids, making them highly nutritious (Muñoz *et al.*, 2013; Bilalis *et al.*, 2016; Felemban *et al.*, 2021). In recent years, the high omega-3 fatty acids content in chia seeds has made them crucial for human health and nutrition, contributing to positive health outcomes (Vuksan *et al.*, 2010). Presently, chia seeds are widely employed in the expulsion of bioactive compounds for the production of functional food items (Bresson *et al.*, 2009). Moreover, the seed's heavy metal levels remained within safe thresholds, and no harmful mycotoxins or gluten were detected (Peiretti & Gai, 2009). The economic significance of chia is expanding in global agriculture because its seeds are rich in proteins, lipids, and ample fiber (Sáez, 2014). Furthermore, socioeconomic studies in Puebla and Mexico have highlighted the importance of chia cultivation in generating income for families. Chia significantly contributes to overall family income and shows higher yields and cost-benefit ratios compared to other crops in certain farming strata (Máximo *et al.*, 2019).

The cultivation of chia is gaining popularity worldwide. There is immense potential for chia cultivation in Bangladesh due to its diverse agroecological zones and growing awareness of healthy dietary practices. Commercial chia cultivation is expanding globally; however, it remains in its early stages in Bangladesh, resulting in significantly lower yields than those observed in other countries. Several factors contribute to these lower yields, with phosphorus (P) fertilization identified as a critical element in addressing this issue. Phosphorus, classified as an essential macronutrient, is vital for facilitating optimal plant growth, especially in enhancing root development. Moreover, it supports assimilating crucial nutrients like sulfur (S), calcium (Ca), and magnesium (Mg) (Lima *et al.*, 2011; Silveira *et al.*, 2015). Phosphorus is crucial for transferring energy, regulating interior cell pressure, and facilitating enzyme dynamism (Souza & Chaves, 2017). Ensuring sufficient phosphorus levels in the initial phases of plant growth is essential to prevent decreased growth, delayed leaf emergence, reduced dry matter production, hindered secondary root development, and seed harm (Souza & Chaves, 2017). Furthermore, P fertilization has improved oil quality in oilseeds (Ramos *et al.*, 2005; Kumari & Saritha, 2017). Zhang *et al.*, (2010) noted that maintaining optimal P levels in the soil results in enhanced agricultural productivity. Phosphorus has been reported to positively impact both vegetative and reproductive development of chia (Hamdi *et al.*, 2022). Research indicates that applying P doses at sowing can lead to increased dry mass of the aerial part, final plant population, mass of grains, productivity, and oil content in chia plants (Nehra & Gahlawat, 2022).

In Bangladesh, intensive farming practices and poor nutrient management have significantly depleted soil fertility, leading to lower crop yields. Phosphorus fixation

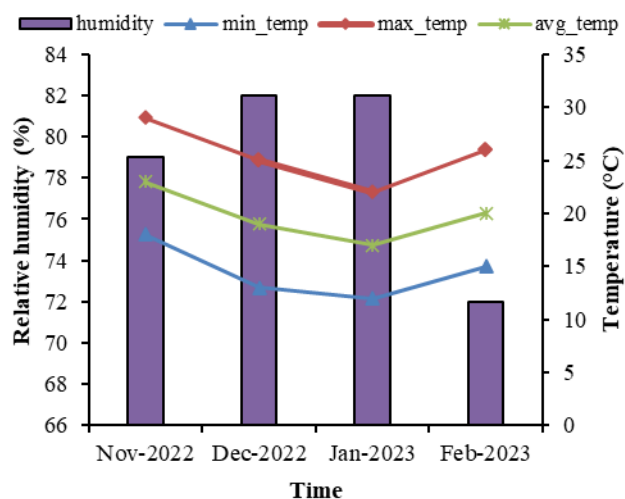
and nutrient depletion pose significant challenges in traditional land use systems, especially in tropical and subtropical soils, where P deficiency severely limits agricultural productivity. Addressing P deficiency is crucial to prevent stunted growth, delayed maturity, poor root development, and yield reductions. Conversely, maintaining optimal phosphorus levels enhances plant vigor, boosts disease resistance, and optimizes the uptake of nitrogen (N) and potassium (K).

Despite its critical role, there is a lack of comprehensive guidance regarding chia management in Bangladesh, including information on soil conditions, ideal planting times, and fertilization practices (Migliavacca *et al.*, 2014). Previous studies have demonstrated that P application can significantly improve various growth parameters and yield components in crops. For example, Lima *et al.*, (2011) reported that P fertilization enhanced root biomass, leaf area, and seed yield in several crops, which can be extrapolated to suggest similar benefits for chia. Silveira *et al.*, (2015) found that P application improved nutrient content and oil quality in oilseeds, indicating similar potential benefits for chia seed quality as well. Given the limited domestic and international research on this study aims to investigate precisely the effects of varying P levels on the growth and production of chia. The objective is to identify the optimal P level for maximizing chia production, thereby addressing the gap in the existing knowledge of chia cultivation and production in Bangladesh.

Materials and Methods

Location and duration: A field experiment was conducted at the field in Boda Upazilla, Panchagarh, Bangladesh from November 2022 to April 2023. The field is situated at 26°05' N latitude and 88°27' E longitude, 63 meters above sea level, within the Old Himalayan Piedmont Plain under Agroecological Zone 1 (AEZ-1) (Anon., 1988).

Weather conditions: During the growing period of the crop, the weather conditions were collected from Weather Yard, Bangladesh Meteorological Department of Bangladesh Agricultural Research Institute, Debiganj, Panchagarh. Here are the details in Fig. 1.



Soil properties: The experimental pot had loam soil with 51.6% sand, 36% silt, and 12.4% clay (Table 1). The soil was acidic (pH 5.42) and had 1.56% organic matter, 0.14% total nitrogen, 67.89 ppm available phosphorus, 0.27 meq.100g⁻¹ soil of exchangeable potassium, and 2.12 ppm of available sulphur.

Experimental treatments and design: The experiment included six treatment groups, each comprising four replications. The treatments were organized in a Randomized Complete Block Design (RCBD). Four blocks were created in an area of 24 × 2 m, and each plot in each block was assigned one of the six treatment combinations. Each plot measured 2 meters by 1 meter, with a gap of 50 cm between blocks and 25 cm between plots. The six treatments used were T₀ = 0 kg P ha⁻¹ (control), T₁ = 20 kg P ha⁻¹, T₂ = 40 kg P ha⁻¹, T₃ = 60 kg P ha⁻¹, T₄ = 80 kg P ha⁻¹, and T₅ = 100 kg P ha⁻¹. The seeds of a local variety of chia were collected from Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh.

Experimentation: The experimental land was irrigated and prepared for chia planting using a series of mechanized farming techniques, including multiple rounds of plowing with a tractor-drawn disc plow, followed by cross-plowing, harrowing, and laddering to achieve a finely tilled soil structure. The previous rice crop stubbles and weeds were removed from the field. The recommended doses of N (90 kg ha⁻¹) and K (75 kg ha⁻¹) were applied, along with six treatments of P (0-100 kg ha⁻¹). The N was applied as urea, P as triple super phosphate (TSP), and K as muriate of potash (MoP). During the concluding stage of land preparation, TSP + MoP and one-third of the urea were administered as initial doses. The remaining two-thirds of urea was distributed after 25 and 50 days of sowing (DAS). Seeds were sown on 09 November 2022. Thinning and gap filling were carried out 15 days after sowing (DAS).

Fig. 1. Daily maximum, minimum, and average temperature and relative humidity during the experimental period.

Weeding was performed twice, first at 25 DAS and then again at 40 DAS. Different intervals were used to apply pesticides, irrigation was carried out during the pre-flowering stage, and proper drainage was ensured. Harvesting was done on 28 February 2023. Seeds were separated, sun-dried for three days, and kept at 12% moisture content. The dried seeds and plants were weighed plot-wise and converted into t ha⁻¹.

Data collection: Data were collected from four designated plants in each plot, including the plant height, number of leaves per plant, the length and count of inflorescences, the number of seeds per inflorescence, seed yield, and biological yield. The harvest index was computed using the following formula:

$$\text{Harvest index \%} = (\text{Seed yield/Biological yield}) \times 100,$$

Where, biological yield = seed yield + straw yield

The soil's physical and chemical characteristics were tested before the start of the experiment and after harvesting the chia plants. These traits comprised pH (determined via a glass electrode pH meter), organic carbon (evaluated through wet oxidation), total nitrogen (assessed using the Micro-Kjeldahl method), available phosphorus (measured via the Olsen method), and mechanical analysis (conducted using the hydrometer method). The soil's textural classification was determined by analyzing the percentages of sand, silt, and clay and fitting them onto Marshall's triangular coordinate system.

Statistical analysis: Data for various parameters were analyzed statistically to determine significant differences in chia growth and yield for different levels of P. Mean values were calculated and treatment means were assessed at a 5% level of significance.

Table 1. Physio-chemical properties of the soil (0-15 cm depth) used for the experiment.

A. Physical properties of the initial soil (0-15 cm depth)

Constituents	Results
Particle size analysis	
Sand (%) (0.2-0.002mm)	51.6
Silt (%) (0.02-0.002mm)	36
Clay (%) (<0.002)	12.4
Soil textural class	Sandy loam

Source: Results obtained from the mechanical analysis of the initial soil analysis

B. Chemical composition of the initial soil (0-15 cm depth)

Characteristics	Analytical value	Critical level	Interpretation	Extraction methods
pH (Soil: water= 1: 25)	5.42	-	Acidic soil	Glass-electrode pH meter method (Page <i>et al.</i> , 1982)
Organic carbon (%)	0.90	-	M	Wet oxidation method (Black, 1965).
Organic matter (%)	1.56	-	M	Calculated by Van Bemmelen factor 1.73 (Piper, 1966)
Total N (%)	0.08	0.12	L	Micro-Kjeldahl method (Bremner and Mulvaney, 1982)
Available P (ppm)	57.89	12.00	L	Molybdate blue ascorbic acid method (Bray and Kurtz, 1945)
Exchangeable K (me/100g soil)	0.27	0.12	M	Determined by Flame photometer
Exchangeable Ca (me/100g soil)	2.50	2.00	VL	Atomic Absorption Spectrophotometer (AAS) (Knudsen <i>et al.</i> , 1982)
Exchangeable Mg (me/100g soil)	2.46	0.50	M	Extractable method (Hunter, 1972)
Available S (ppm)	2.12	10.00	L	Turbidity method using BaCl ₂ (Fox <i>et al.</i> , 1964)
Available B (ppm)	0.18	0.20	L	Mono-calcium bi-phosphate method, determined by Spectro-photometer following Azomethine H method (Page <i>et al.</i> , 1982)
Available Zn (ppm)	0.84	0.60	M	AAS (Lindsay & Norvell, 1978)
Available Fe (ppm)	46.22	4.00	M	AAS (Lindsay & Norvell, 1978)

Available Mn (ppm)	10.33	1.00	H	AAS (Lindsay & Norvell, 1978)
CEC (me/100 g soil)	6.2	-	-	Sodium acetate saturation method (Rhoades, 1982)

Source: Results obtained from the chemical analysis of the initial soil sample from SRDI, Dinajpur; H: High, L= Low, M: Medium, VL: Very Low

Results and Discussion

Morphological characteristics of chia

Plant height (cm): The plant height and number of leaves are crucial factors that impact the growth and yield of chia plants. Different levels of P dose (0, 20, 40, 60, 80, and 100 kg P ha⁻¹) showed significant effects on the plant height, as shown in Table 2. Among the experimental treatments, T₃ exhibited the tallest plant at 105.24 cm when the plant was grown with P (60 kg ha⁻¹), statistically comparable (103.50 and 101.02 cm) to treatments T₄ (80 kg P ha⁻¹) and T₅ (100 kg P ha⁻¹), respectively. On the contrary, the treatment T₀, which received no phosphorus application, displayed the shortest plant height (68.79 cm). These results align with the previous report of Chan (2016). Naomi *et al.*, (2014) indicated that *Salvia officinalis* had the greatest height when fertilized with 60 kg P ha⁻¹. P application plays a significant role in influencing the growth of chia plants. Research indicates that P positively impacts the vegetative and reproductive development of chia, leading to increased plant height (Souza & Chaves, 2017; Domingues *et al.*, 2019).

Number of branches plant⁻¹: Different levels of P resulted in significant variations in the number of branches per plant (NBPP). However, the T₃ treatment resulted in the highest NBPP (30.50) and was statistically comparable to that observed in the T₄ treatment (28.75). The lowest NBPP (10.75) was observed with Treatment T₀ (Table 2). This result is consistent with the findings by Kumar *et al.*, (2014). The application of P has been shown to have a significant effect on the growth and development of chia plants, particularly in terms of the number of branches. Research conducted on chia cultivation has demonstrated that different doses of P, along with biofertilizers, can lead to increased vegetative growth of chia plants, resulting in higher NBPP (Domingues *et al.*, 2020). Additionally, studies focusing on the gene expression responsible for lipid synthesis in chia plants have highlighted the importance of P rates application in lipid metabolism, which can further influence the plant's overall growth and branching patterns (Silva *et al.*, 2021). Our findings underscore the crucial role of P in promoting branching and overall productivity in chia plants, emphasizing the significance of proper fertilization strategies for optimal cultivation outcomes.

Number of leaves plant⁻¹ The number of leaves per plant (NLPP) is a crucial morphological trait for plant growth and development, given that leaves serve as the primary photosynthetic organs. The different doses of P significantly affected the NLPP (Table 2). The application of T₃ treatment involving P at 60 kg ha⁻¹ resulted in the highest NLPP (54.25), statistically comparable to the T₄ (53.50 g) and T₅ (50.25 g) treatments which incorporated P at 80 and 100 kg ha⁻¹, respectively. Conversely, the lowest NLPP (22.75) was observed with T₀, where no P was applied. The data indicated that increasing the dose of P application correspondingly increased the NLPP (Table 2). The application of P has been shown to have a positive impact on the development of chia plants, influencing various growth parameters like plant height and NBPP. Different doses of P led to an increased dry mass of the

aerial parts of chia plants (Souza and Chaves, 2017), indicating higher foliage production. These findings suggest that P plays a crucial role in enhancing the overall growth of chia plants, indicating a significant correlation between P application and the number of leaves in chia plants. Although specific data on the number of leaves was not explicitly mentioned, the results imply that higher P levels contribute to better plant growth and development.

Table 2. Impact of variant levels of P on the morphological characteristics of Chia.

Treatments	Plant height (cm)	Number of branches plant ⁻¹	Number of leaves plant ⁻¹
T ₀ (Control)	68.79 d	10.75 d	22.75 d
T ₁ (20 kg P ha ⁻¹)	79.60 c	15.25 c	32.75 c
T ₂ (40 kg P ha ⁻¹)	88.33 b	22.50 b	42.75 b
T ₃ (60 kg P ha ⁻¹)	105.24 a	30.50 a	54.25 a
T ₄ (80 kg P ha ⁻¹)	103.50 a	28.75 a	53.50 a
T ₅ (100 kg P ha ⁻¹)	101.02 a	26.00 ab	50.25 ab
LSD	14.09	4.68	9.86
CV %	8.49	11.58	2.39

Figures with similar letters in the column exhibit no significant differences at a 5% probability level; LSD: Least significant differences, CV: Coefficient of variations

Table 3. Impact of variant levels of P on the growth characteristics of Chia.

Treatments	Fresh weight of plants (t ha ⁻¹)	Dry weight of plants (t ha ⁻¹)
T ₀ (Control)	1.65 c	1.17 c
T ₁ (20 kg P ha ⁻¹)	2.70 b	1.98 b
T ₂ (40 kg P ha ⁻¹)	2.78 b	2.27 ab
T ₃ (60 kg P ha ⁻¹)	3.18 a	2.52 a
T ₄ (80 kg P ha ⁻¹)	2.99 a	2.43 a
T ₅ (100 kg P ha ⁻¹)	2.92 ab	2.33 ab
LSD	0.24	0.26
CV %	4.94	6.98

Figures with similar letters in the column exhibit no significant differences at a 5% probability level; LSD: Least significant differences, CV: Coefficient of variations

Growth characteristics of chia

Fresh weight (t ha⁻¹): The fresh weight (FW) of the chia plant was significantly influenced by different levels of P fertilizer. The effect of P on the FW is presented in Table 3. The highest FW was observed in T₃ (3.18 t ha⁻¹) which was statistically similar to that of T₄ (2.99 t ha⁻¹) and T₅ (2.92 t ha⁻¹). The lowest FW was recorded (1.65 t ha⁻¹) with T₀ having no P fertilizer application. A similar result was found by Kumar *et al.*, (2014). P significantly increased the FW of chia plants, likely by enhancing root growth, which in turn improves water and nutrient uptake (Table 6). This increased nutrient availability supports vigorous plant development and higher biomass production. P is crucial for energy transfer and photosynthesis, which are vital processes for plant tissue development and growth. This may ultimately lead to an increased FW in chia plants.

Dry weight (t ha⁻¹): The different levels of P fertilizer significantly affected the dry weight (DW) of the chia plant. However, the highest DW was observed with T₃ (2.52 t ha⁻¹), which was statistically identical with T₄ (2.43 t ha⁻¹) and T₅ (2.33 t ha⁻¹). The lowest DW was recorded as (1.17 t ha⁻¹) in the T₀ treatment with no P fertilizer

application (Table 3). Souza & Chaves (2017) investigated that 75 kg P₂O₅ provides higher plant dry matter in chia. In its inorganic form, P is essential for various enzymatic reactions, such as photosynthesis and carbohydrate

metabolism, as well as for regulating metabolic pathways and the synthesis of starch and sucrose.

Table 4. Impact of variant levels of P on the yield traits of Chia.

Treatments	No. of inflorescence plant ⁻¹	Length of inflorescence	No. of seeds inflorescence	1000-seed weight (g)
T ₀ (Control)	16.05 d	7.52 d	357.10 c	1.17 d
T ₁ (20 kg P ha ⁻¹)	18.95 c	8.84 c	409.20 bc	1.20 c
T ₂ (40 kg P ha ⁻¹)	19.85 bc	11.89 ab	439.50 b	1.22 bc
T ₃ (60 kg P ha ⁻¹)	24.63 a	13.60 a	522.30 a	1.27 a
T ₄ (80 kg P ha ⁻¹)	21.86 ab	11.24 b	469.04 ab	1.25 ab
T ₅ (100 kg P ha ⁻¹)	21.65 ab	10.48 bc	430.31 b	1.21 bc
LSD	0.02	1.970	6.64	0.02
CV %	0.05	12.34	9.19	0.84

Figures with similar letters in the column exhibit no significant differences at a 5% probability level; LSD: Least significant differences, CV: Coefficient of variations

It also facilitates triphosphate transport and sugar translocation (Mitra *et al.*, 1993; Domingues *et al.*, 2020), which are critical for overall metabolic activity and plant growth. Thus, P fertilization enhances these processes, likely leading to increased dry matter production in chia plants through enhanced energy transfer, nutrient utilization, and biomass accumulation. Alsafar *et al.*, (2009) reported comparable findings in indigenous mint (*Mentha arvensis* L.). Moreover, P positively impacts chia plant development, enhancing various growth parameters. These findings indicate that P plays a crucial role in increasing overall growth and productivity, significantly correlating with increased dry matter production in chia plants. Our results align with the findings of Frantz (2013), who reported that phosphorus supplementation increased shoot mass in other crops, such as *Zinnia* (*Zinnia elegans*) and *Vinca* (*Catharanthus roseus*).

Yield traits of chia

Number of inflorescence plant⁻¹: The different levels of P application showed a significant effect on the number of inflorescence plant⁻¹ (NIPP) of chia (Table 4). The maximum NIPP (24.63) was recorded in the T₃ treatment which was statistically similar to the T₄ treatment (21.86) and T₅ treatment (21.65). The minimum NIPP was recorded in the T₀ treatment (16.05). Banjana (2016) discovered that applying P₂O₅ @ 60 kg ha⁻¹ resulted in the maximum NIPP of chia. Souza and Chaves (2017) found that phosphate fertilization significantly increased the number of inflorescences in chia plants, achieving a maximum of 8.58 inflorescences per plant with the highest dose (100 kg ha⁻¹ P). P enhances inflorescence development in chia plants by stimulating plant growth, including factors such as plant height and the number of leaves (Table 2), as well as increasing dry matter production (Table 3). These effects contribute to greater flower formation, supporting overall plant vigor and reproductive processes, thereby increasing inflorescence production.

Effective length of inflorescence: Application of P showed a significant difference in the effective length of inflorescence plant⁻¹ (LIPP) of chia (Table 4). The longest inflorescence (13.60 cm) was recorded with T₃ treatment

while the shortest inflorescence (7.52 cm) was recorded with T₀. A similar result was reported by Banjana (2016). Chan (2016) indicated that 30 kg ha⁻¹ and 60 kg ha⁻¹ favored greater cluster length in chia. P increases the length of inflorescences in chia plants by promoting cell division and elongation processes in the growing tissues. This supports enhanced floral development, resulting in longer inflorescences as a physiological response.

Number of seeds inflorescence⁻¹: The different P levels significantly affected the number of seeds inflorescence⁻¹ (NSPI) of chia (Table 4). The highest NSPI (522.3) was recorded with the T₃ treatment which was statistically identical with the T₄ treatment (469.04). The lowest NSPI was recorded (357.0) in T₀ where no P was applied which was statistically similar to T₁ (409.20). Research by Domingues *et al.*, (2020) has shown that the application of phosphorus can significantly enhance both vegetative and reproductive growth, which in turn positively impacts the seed yield of chia plants. The soil addition of P enhanced plant growth by promoting factors such as plant height, number of branches, and leaves per plant (Table 2), as well as enhancing dry matter production (Table 3) and the length of inflorescences (Table 4). These improvements likely enhanced plant development by providing greater resources and structural support, which in turn promoted higher flower production and an increased number of seeds per inflorescence in chia plants.

Thousand seed weight (g): Thousand seeds weight (TSW) of chia response to different levels of P application and was represented in Table 3. A significant variation was observed in the TSW of chia with the application of different doses of P. The highest value of TSW (1.27 g) was obtained with the T₃ treatment which was statistically similar to that of the T₄ (1.25 g). The lowest value of TSW (1.17 g) was recorded with the T₀ treatment. The results are consistent with the findings of Domingues *et al.*, (2020) who demonstrated that P fertilization significantly increased the TSW in chia plants. Khatun (2021) found that the application of P @ 35 kg ha⁻¹ produced the highest TSW in mustard. The results are similar to those found by Dourado *et al.*,

(2001), who observed that increasing P doses affected the TSW of crotalaria (*Crotalaria juncea* L.). P increases the TSW in chia plants by promoting enhanced seed development and filling, resulting in larger and heavier seeds. P likely supported essential metabolic processes

involved in dry matter production, seed formation, and maturation, thereby contributing to an increase in TSW as a physiological response.

Table 5. Impact of variant levels of P on the yield indices of Chia.

Treatments	Seed yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Biological yield (t ha ⁻¹)	Harvest index (%)
T ₀ (Control)	0.19 d	1.18 e	1.37 c	13.87 c
T ₁ (20 kg P ha ⁻¹)	0.31 c	1.64 c	1.95 b	15.90 bc
T ₂ (40 kg P ha ⁻¹)	0.34 bc	1.77 b	2.11 ab	16.11 b
T ₃ (60 kg P ha ⁻¹)	0.44 a	2.03 a	2.47 a	17.81 a
T ₄ (80 kg P ha ⁻¹)	0.39 ab	1.79 b	2.18 ab	17.88 a
T ₅ (100 kg P ha ⁻¹)	0.37 ab	1.80 c	2.09 b	17.05 a
LSD	0.02	0.03	0.02	0.04
CV %	3.45	0.92	0.58	0.12

Figures with similar letters in the column exhibit no significant differences at a 5% probability level; LSD: Least significant differences, CV: Coefficient of variations

Table 6. Varying P levels affect the total N, available P, exchangeable K, and available S of the post-harvest soil.

Treatments	Total N (%)	Available P (ppm)	Exchangeable K (meq 100 g ⁻¹ soil)	Available S (ppm)
T ₀ (Control)	0.06	58.67 e	0.32 c	1.85 e
T ₁ (20 kg P ha ⁻¹)	0.07	64.69 d	0.33 c	5.82 d
T ₂ (40 kg P ha ⁻¹)	0.08	66.73 cd	0.34 c	6.28 c
T ₃ (60 kg P ha ⁻¹)	0.09	73.42 b	0.48 b	7.27 b
T ₄ (80 kg P ha ⁻¹)	0.09	78.60 ab	0.53 a	7.89 a
T ₅ (100 kg P ha ⁻¹)	0.10	83.30 a	0.47 b	8.01 a
LSD	0.06	7.34	2.47	0.34
CV %	8.60	6.95	9.80	3.70

Figures with similar letters in the column exhibit no significant differences at a 5% probability level; LSD: Least significant differences, CV: Coefficient of variations

Yield indices of Chia

Seed yield (t ha⁻¹): The impact of different levels of P on seed yield (SY) of chia is represented in Table 5 which shows a positive relationship between different levels of P application and SY. Significant variation was observed in the SY of chia with the application of different doses of P. The highest SY (0.44 t ha⁻¹) was recorded with the T₃ treatment, which was statistically identical to that of the T₄ treatment (0.39 t ha⁻¹). The lowest SY (0.19 t ha⁻¹) was recorded in T₀. This finding is confirmatory with Chia yield increased linearly with higher P application rates, similar to findings by Mary *et al.*, (2018) and Domingues *et al.*, (2020) in chia plants. P fertilization also increased seed yield in other crops, such as soybeans (Kumar *et al.*, 2014; Noori *et al.*, 2015), and beans (*Phaseolus vulgaris* L.) (Zucareli *et al.*, 2006). This is plausible as P is essential for cellular energy transfer, respiration, photosynthesis, and structural functions in plants (Taiz & Zeiger, 2013). Therefore, the deficiency of P can restrict crop growth and productivity (Santos & Kliemann, 2005).

Straw yield (t ha⁻¹): The influence of different levels of phosphorus application on the straw yield (StY) of chia was significant, as depicted in Table 5. However, the T₃ treatment resulted in the greatest StY (2.03 t ha⁻¹). The StY with the T₄ treatment was 1.79 t ha⁻¹, comparable to that of the T₂ treatment (1.77 t ha⁻¹). In contrast, the lowest StY (1.18 t ha⁻¹) was recorded with the T₀ treatment where no P

was applied. Application of P increased the StY in chia crops by enhancing overall plant growth and development, including plant height, number of branches and leaves (Table 2), number and length of inflorescences (Table 4), and dry matter production (Table 3). Improved nutrient uptake and photosynthesis also contributed to increased biomass production, resulting in a higher straw yield. The application of P can result in notable increases in the dry mass of the aerial parts, productivity, and oil content of chia plants (Domingues *et al.*, 2020). Additionally, P plays a crucial role in enhancing the photosynthetic rate, transpiration, and overall biomass accumulation in chia plants (Lovelli *et al.*, 2019).

Biological yield (t ha⁻¹): Different levels of P application showed a significant impact on the biological yield (BY) of chia (Table 5). However, the highest value of BY (2.47 t ha⁻¹) was recorded with the T₃ treatment which was statistically identical to T₄ (2.18 t ha⁻¹) and T₂ (2.11 t ha⁻¹). The lowest BY (1.37 t ha⁻¹) was recorded with T₀ where no P was applied. P increased the BY of chia by enhancing plant growth, including height, branching, leaf production (Table 2), inflorescence length and number (Table 4), and dry matter production (Table 3), leading to greater biomass production. Bonfim-Silva *et al.*, (2011) reported that adequate levels of phosphorus (P) not only promote leaf area expansion but also enhance plant height, leaf emergence, and growth, facilitating increased capture of solar radiation and

production of photoassimilates. These factors likely contributed to an increase in biomass yield.

Harvest Index (%): In agriculture, the term ‘harvest index’ (HI) is employed to measure the yield of a crop species relative to the overall biomass generated. It was observed that the HI (%) of chia was significantly affected by different P levels (Table 5). Nonetheless, the T₃ treatment (60 kg P ha⁻¹) achieved the maximum HI of 17.88%, which was statistically identical to that of the T₃ treatment (17.81%). Conversely, the T₀ treatment, which received 0 P fertilization exhibited the lowest HI at 13.87%. According to Sisie & Mirshekari (2011), the application of phosphorus fertilizer significantly increased the harvest index, with higher phosphorus levels leading to improved harvest indices and seed yield. The application of P increased the HI in chia crops by enhancing reproductive efficiency and seed yield relative to total biomass. This nutrient supports optimal seed formation and development, resulting in a higher proportion of harvested seeds compared to vegetative biomass.

Chemical properties of the collected soil after harvesting: The application of P fertilizer influenced soil chemical properties. Table 6 shows that the post-harvest soil contains consistent total nitrogen (N) levels across all treatments. However, the highest N content in the soil was found in treatments T₃, T₄, and T₅, which measured at 0.09, 0.09 and 0.10%, respectively. The control treatment (T₀) exhibited the lowest N content. Treatment T₅ showed the highest P content at 83.3 ppm, whereas the lowest P content (58.67 ppm) was observed in treatment T₀. The increase in phosphorus (P) content in post-harvest soil after application in a chia field is likely due to residual P from the fertilizer not fully utilized by the chia plants during their growth. This unused P remains in the soil, contributing to higher P content after harvest. The maximum exchangeable potassium (K) was found in the treatment T₄ (0.53 meq 100 g⁻¹ soil). The lowest (0.32 meq 100 g⁻¹ soil) K content was noticed in the T₀ treatment. The treatment T₅ resulted in the highest soil sulfur (S) content (8.01 ppm), while the control treatment

T₀ had the lowest S content at 1.85 ppm. P application in a chia field can indirectly increase K and S content in post-harvest soil by enhancing overall soil fertility and nutrient availability, which can stimulate microbial activity and organic matter decomposition, releasing K and S from organic sources into the soil solution. The application of P in chia crops has shown positive effects on the availability of N, P, K, S, Mg, and Ca in the soil, enhancing the overall nutritional quality and supporting nutrient mobilization (Prakash *et al.*, 2022; Dimkpa *et al.*, 2023). Research on nutrient mobility in soil profiles of cotton crops found that higher NPK application levels increased the concentrations of available N, P, and K, demonstrating the impact of nutrient levels on soil nutrient availability and mobility (Sathya *et al.*, 2008).

Heatmap correlation: The heatmap illustrates the Pearson correlation coefficients between various agronomic traits, providing a visual summary of their interrelationships. Each cell in the matrix represents the correlation coefficient between a pair of traits, with the color intensity reflecting the strength of the correlation. The result of the present study's heatmap analysis is displayed in Fig. 2. PH and NL show a very strong positive correlation ($r = 1$), suggesting that taller plants have more leaves. Similarly, NBPP and NIPP are strongly correlated ($r = 0.95$), indicating that plants with more branches tend to produce more inflorescences. ELIS and NSPI also show a strong positive correlation ($r = 0.95$), suggesting that longer inflorescence is associated with more seeds per inflorescence. Other significant positive correlations include FW and SY ($r = 0.97$), and DWP and SY ($r = 0.97$), highlighting that plants with higher fresh and dry weights yield more grain. Additionally, TSW is positively correlated with SY ($r = 0.93$) and StY ($r = 0.89$), suggesting that larger seed weight is linked with higher grain and straw yields. Overall, most traits exhibit moderate to strong positive correlations with each other. Improving one trait could positively impact others, thereby enhancing overall crop performance. These results are in agreement with earlier findings of Islam *et al.*, (207a, 2021a,b, 2023), Islam *et al.*, (2024), Sayed *et al.*, (2024).

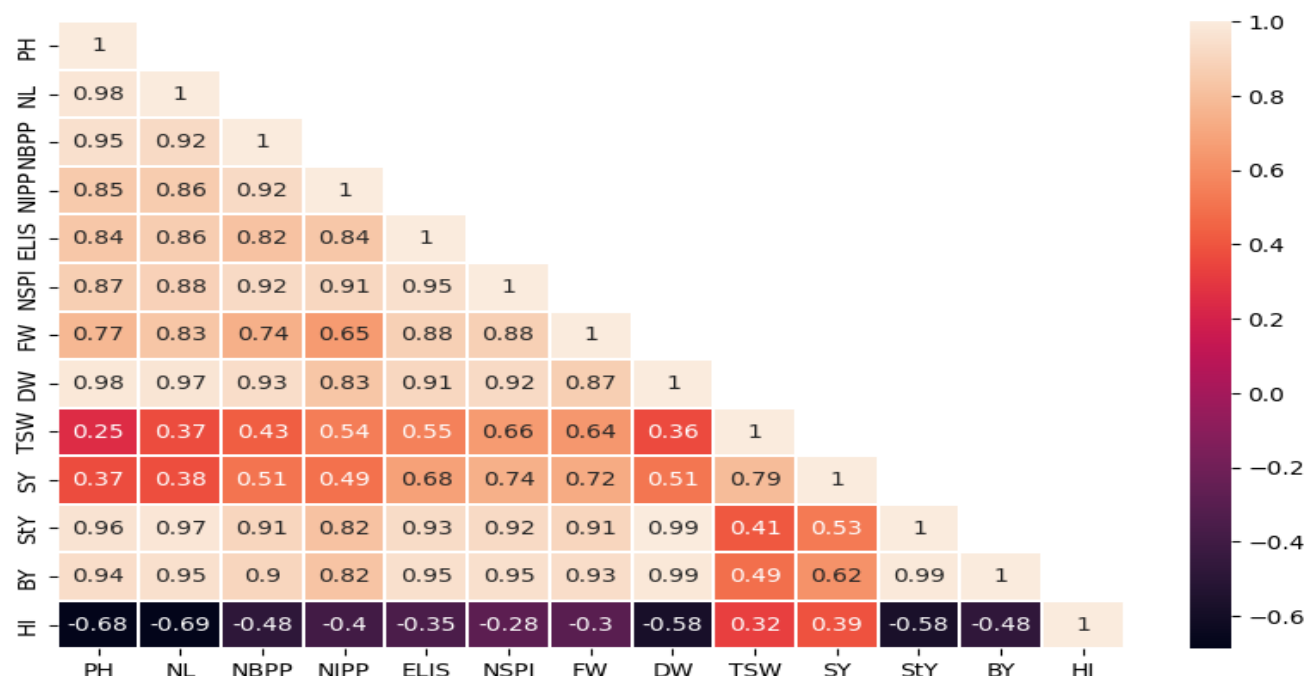


Fig. 2. Heatmap showing the Pearson correlation coefficients between various agronomic traits. The color intensity indicates the strength of the correlation, with lighter colors representing stronger positive correlations. PH= Plant height, NL= Number of Leaf, NBPP= Number of branches plant⁻¹, NIPP= Number of inflorescence plant⁻¹, ELIS= Effective length of inflorescence, NSPI= Number of seeds per inflorescence, FW=Fresh weight of plants, DW= Dry weight of plants, TSW=1000-seed weight, SY= Seed yield, StY= Straw yield, BY= Biological yield, HI= Harvest index

Conclusions

The findings from the present study indicated that the application of P fertilizer to Chia plants improved the growth and seed production compared to the control treatment. Applying 60 kg ha⁻¹ phosphorus (P) significantly improved the morphology, growth, yield, and soil properties in chia fields. Key traits such as plant height, leaf number per plant, branch number per plant, fresh and dry weights, number of inflorescences per plant, inflorescence length, seeds per inflorescence, and 1000-seed weight were the highest. Moreover, the yield indices including seed yield, stover yield, and biological yield were also increased. This suggests that the application of P at the rate of 60 kg ha⁻¹ is the most effective rate for improving the growth and production of chia in the particular agricultural region of Bangladesh. Higher P levels improved soil nutrients, with 60 kg ha⁻¹ being the most economical for AEZ-1 in Bangladesh. This study was conducted using a specific soil type. Further trials are necessary across diverse geographical regions to provide accurate fertilizer recommendations.

Acknowledgments

The authors would like to acknowledge Prof. Dr. Md. Monsur Rahman, Department of Soil Science, HSTU, Dinajpur, Bangladesh for his kind help in the experimentation. This article is derived from a research grant funded by the Research, Development, and Innovation Authority (RDIA) - Kingdom of Saudi Arabia with grant number (13445-Tabuk-2023-UT-R-3-1-SE).

Funding: This article is derived from a research grant funded by the Research, Development, and Innovation

Authority (RDIA) - Kingdom of Saudi Arabia with grant number (13445-Tabuk-2023-UT-R-3-1-SE).

Conflicts of Interest: The authors declare no conflict of interest.

Author's Contribution: Conceptualization, A.K.M.M.H. and M.H.A.; methodology, A.K.M.M.H., M.H.A. and K.K.V.; investigation (data collection), M.H.A., M.A.M., and K.K.V.; formal analysis, M.H.A., M.M.I., M.J.I., and M.H.P., A.S.A., M.S.I.; data interpretation, M.H.A., M.J.I., A.S.A., and M.M.R.; writing-original draft preparation, M.H.A., M.A.M., A.M.M., A.S.A., and M.S.I.; writing-review and editing, M.S.I., S.T.A., Z.E., M.E., M.H., H.A. and M.S.I. All authors have read and agreed to the published version of the manuscript.

Funding: The funding for this experiment was provided by the National Science and Technology, Grant # 34521, Ministry of Science and Technology, Govt. Peoples Republic Bangladesh, Dhaka, Bangladesh. The authors extend their appreciation to the Researchers supporting project number (RSPD2025R561) King Saud University, Riyadh, Saudi Arabia.

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