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Growth and yield response of Chinese kale to nitrogen fertilization across contrasting tropical soil textures

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Abstract: Efficient nitrogen (N) management is critical for optimizing leafy vegetable production under contrasting soil conditions. A greenhouse experiment was conducted at Mahasarakham University, Thailand, to evaluate the growth, yield, and N use efficiency of Chinese kale (*Brassica oleracea* var. *alboglabra*) grown in loamy sand and clay soils under four N rates applied as urea (46% N): 0, 0.32, 0.64, and 0.96 g pot^{-1}. Growth and yield responses differed between soil textures; clay supported greater overall biomass accumulation, whereas loamy sand produced higher shoot fresh weight, reflecting differences in soil fertility and nutrient availability. Increasing urea rates enhanced chlorophyll (SPAD) content and biomass, with the highest values recorded at 0.96 g pot^{-1}. Pearson's correlation analysis showed strong positive associations among biomass traits ($r > 0.90^{***}$), moderate correlations with chlorophyll content, and weak or nonsignificant correlations for leaf number. Principal component analysis indicated that biomass-related traits dominated PC1 (61.9%), while leaf number contributed mainly to PC2 (14.1%), effectively separating samples by soil texture. Nitrogen use efficiency was optimized at 0.32 g pot^{-1} in loamy sand and at 0.96 g pot^{-1} in clay, underscoring the need for soil-specific nutrient management. Overall, the results identify biomass traits as reliable indicators of yield potential and highlight the value of targeted N management for improving Chinese kale production in tropical soils.

Keywords: Chinese kale; nitrogen fertilization; urea; loamy sand; clay soil.

Abbreviations: ANOVA _Analysis of variance; CV_ Coefficient of variation; EC_Electrical conductivity; LSD_Least significant difference; N_Nitrogen; OM_Organic matter; P_Phosphorus; K_Potassium; NUE_Nitrogen use efficiency; PCA_ Principal component analysis

Introduction

Chinese kale (*Brassica oleracea* L. var. *alboglabra*) is an important leafy vegetable widely cultivated in Southeast Asia, especially in Thailand, because of its nutritional value and economic significance. It is grown year-round for domestic consumption and export to neighboring countries, with an estimated annual production value of more than 250 million baht (DOAE, 2020). Nutritionally, Chinese kale is a good source of protein, calcium, iron, vitamins A, C, and K, as well as dietary fiber. It also contains beneficial phytochemicals such as glucosinolates, carotenoids, and phenolic compounds, which contribute to antioxidant, anti-inflammatory, and disease-preventive properties (Liu, 2013; Sanlier and Guler, 2018; Li et al., 2025). These attributes emphasize its importance as both a nutritious vegetable and a high-value horticultural crop in Thailand.

Chinese kale grows optimally at temperatures of 25–30 °C under tropical conditions in fertile, well-drained soils with full sunlight (DAF, 2010). Among essential nutrients, nitrogen (N) is particularly critical for leafy vegetables. It is a structural component of amino acids, proteins, nucleic acids, and chlorophyll, and it is central to key enzymes such as nitrate reductase and Rubisco that regulate metabolism and photosynthesis (Marschner, 2012; Taiz et al., 2015). Adequate N supply promotes vegetative growth, leaf expansion, and biomass accumulation, while deficiency reduces yield and leaf quality. Conversely, excessive N application lowers N use efficiency (NUE) and increases environmental risks (Liu et al., 2018).

The positive response of Brassica crops to N fertilization has been well documented. For instance, Chakwizira et al. (2015) reported a fourfold increase in Chinese kale dry matter yield with 500 kg N ha^{-1} compared with unfertilized plants. In Chinese cabbage, Cao et al. (2023) found that 250 kg N ha^{-1} produced the maximum yield, while Gebeyaw and Belete (2020) observed the highest head weight at 150 kg N ha^{-1}. More recently, Suphachai et al. (2006) demonstrated that leafy vegetables, including kale and pak choi, achieved maximum growth and NUE at approximately 156 kg N ha^{-1}. These findings emphasize the importance of optimizing nitrogen fertilization but also reveal variability in crop responses depending on species and growing environment (Xu et al., 2012).

In Thailand, Chinese kale is mainly cultivated in the Central and Northeastern regions. The Central region is characterized by fertile clay and alluvial soils, whereas the Northeast is dominated by loamy sand and sandy paddy soils that are inherently low in fertility and susceptible to nutrient leaching (Vityakon, 2005). In addition, in the Northeastern region such as in the province of Khon Kaen, alluvial fine textured soils are also used for production of vegetable crops including Chinese kale as they are more fertile than the typical coarse-textured soils of the region (Vityakon et al., 1988). Such contrasting soil textures influence nutrient retention and availability, leading to differential crop responses to fertilizer application. This was shown by lower yield response to cow manure application of the Chinese kale grown in sandy loam textured rice paddy soil than that grown in silty clay loam textured alluvial soil in Khon Kaen (Vityakon et al., 1988). The inherently low fertility and weak nutrient-holding capacity of loamy sand soils, in particular, constrain vegetable production and underscore the need for efficient nutrient management strategies (Vityakon, 2005; Dong et al., 2012).

Therefore, the objective of this study was to investigate the effects of different N fertilization levels on the growth and yield of Chinese kale cultivated under two contrasting tropical soil textures: loamy sand and clay. It was hypothesized that N fertilization would significantly enhance crop performance, with greater responses expected in loamy sand due to its lower inherent fertility and nutrient-holding capacity.

Results and discussion

Soil properties before Chinese kale transplanting

The loamy sand soil had a pH of 5.85, electrical conductivity (EC) of 0.06 dS m^{-1}, organic matter (OM) content of 0.10%, total N of 0.05%, available phosphorus (P) of 13.0 mg kg^{-1}, and exchangeable potassium (K) of 100.0 mg kg^{-1} (Table 1). This soil was slightly acidic, non-saline, with very low N, moderate P, and low K, indicating low fertility (Dobermann and Fairhurst, 2000). Such conditions are typical of coarse-textured soils in Northeast Thailand, where rapid nutrient leaching reduces fertility and crop productivity (Vityakon, 2005).

The clay soil had a pH of 5.02, EC of 0.17 dS m^{-1}, OM content of 0.40%, total N of 0.08%, available P of 3.5 mg kg^{-1}, and exchangeable K of 60.0 mg kg^{-1} (Table 1). This soil was moderately acidic and non-saline, but contained very low N, low P, and low K, reflecting overall very low fertility (Dobermann and Fairhurst, 2000). These properties are consistent with highly weathered tropical clays, which often exhibit low OM and strong P fixation (Sanchez, 2003).

According to Sanchez (2003), both soils were classified as infertile, primarily due to insufficient N availability to sustain vigorous crop growth. This underscores the importance of effective N management to improve nutrient availability and support vegetable production in tropical agroecosystems (Liu et al., 2018).

Growth and yield attributes of Chinese kale

Plant height was not significantly affected by soil texture, N rates, or their interaction at 7 and 14 DAT. At 25 DAT, however, significant effects of soil texture, N application, and their interaction were observed (Table 2). Plants grown in loamy sand (14.80 cm) were taller than those in clay (13.20 cm), reflecting better aeration and nutrient availability in loamy soils (Sanchez et al., 2003; Fageria, 2009; Brady and Weil, 2017). Nitrogen fertilization also increased plant height, with the tallest plants (16.33 cm) at 0.96 g urea pot^{-1}, significantly higher than the control (12.88 cm), confirming the positive response of Brassica crops to N supply (Yeshiwas, 2017; Muhammad et al., 2024). The soil × N interaction showed that loamy sand with N4 (0.96 g urea pot^{-1}) produced the tallest plants (16.67 cm), while the shortest plants were in clay with N3 (11.67 cm).

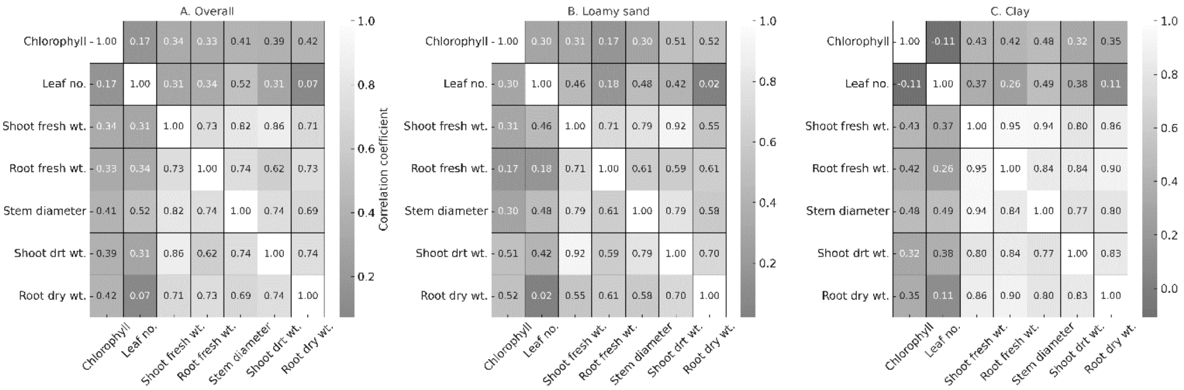

Figure 1. Correlation heatmaps of Chinese kale traits for (A) all samples, (B) loamy sand, and (C) clay. Darker shading indicates stronger positive or negative correlations among traits. Data represent means of two growing seasons (February–March 2024 and 2025).

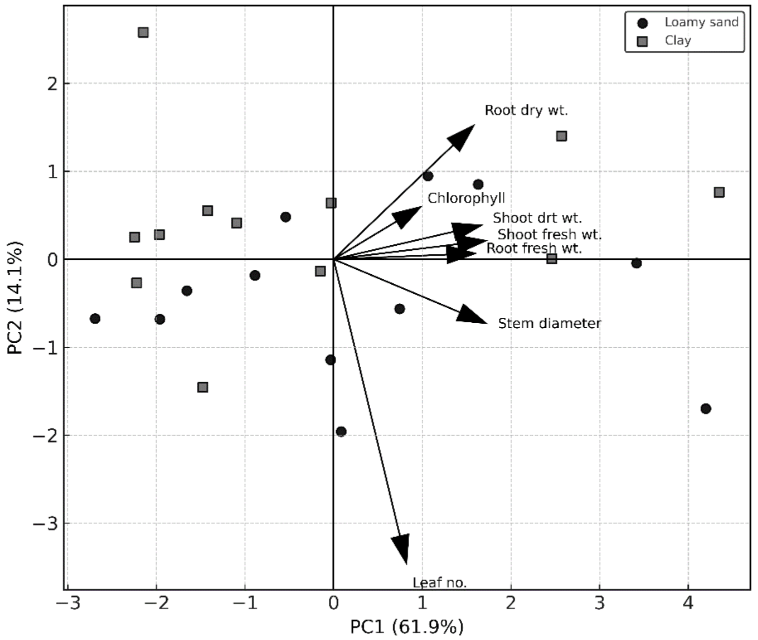

Figure 2. Principal component analysis (PCA) biplot of Chinese kale traits across loamy sand and clay soils. PC1 (61.9%) and PC2 (14.1%) together explained 76.0% of the total variation. The biplot shows that loamy sand and clay treatments are clearly separated along PC1, indicating differences in overall growth responses between soil textures. Vectors represent trait contributions, with shoot and root biomass closely associated and positively influencing PC1, while leaf number loads negatively on PC2. Data represent means of two growing seasons (February–March 2024 and 2025).

Leaf number per plant was not significantly influenced by soil texture, N rate, or their interaction at any sampling time (Supplementary Table S1). At 25 DAT, loamy sand produced slightly more leaves (6.99 leaves plant^{-1}) than clay (6.30 leaves plant^{-1}), although the difference was not statistically significant. Nitrogen application showed a modest increasing trend, with the highest rate (N4) producing the greatest leaf number (7.17 leaves plant^{-1}) compared with the control (5.67 leaves plant^{-1}). Similar nonsignificant responses of leaf number to N fertilization have been reported in *Brassica oleracea* and spinach (Treadwell et al., 2007; Khan et al., 2009; Yeshiwas, 2017).

Chlorophyll (SPAD) content was not significantly affected at 14 DAT, as none of the main factors or their interaction were significant (Table 3). At 25 DAT, soil texture and the soil × N interaction significantly influenced SPAD values, whereas the main effect of N was nonsignificant. Loamy sand recorded higher SPAD (49.25) than clay (45.34). Across N levels, SPAD values ranged from 40.75 to 53.65, with the highest value observed at 0.96 g urea pot^{-1} (N4). These findings agree with previous reports that nitrogen enhances chlorophyll synthesis and photosynthetic efficiency in leafy vegetables (Netto et al., 2005; Kalaji et al., 2017). The interaction pattern showed that loamy sand combined with N2 (56.23) and N4 (55.37) produced the highest SPAD values, whereas clay with N3 (31.88) had the lowest. In addition, a paired t-test indicated no significant temporal difference in SPAD between 14 and 25 DAT ($t = 0.83$, $p = 0.414$) (Supplementary Table S2).

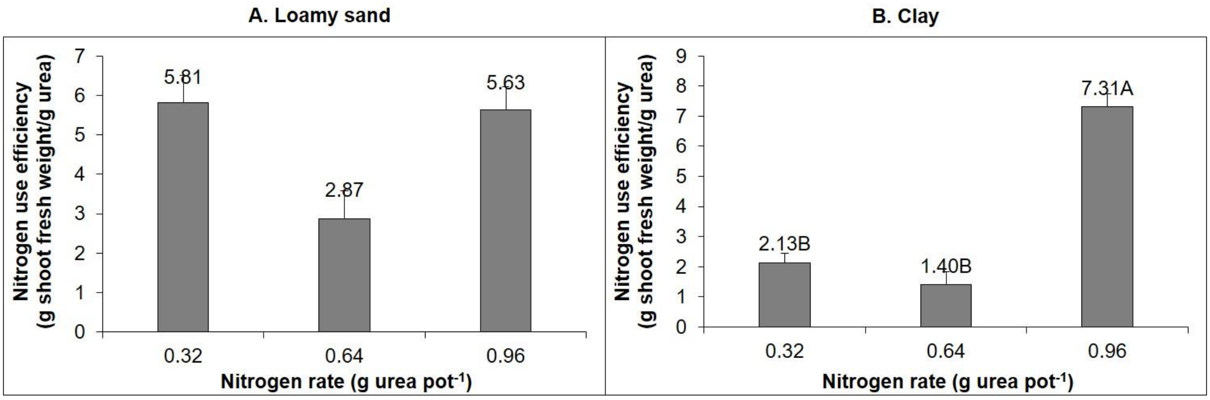

Figure 3. Agronomic nitrogen use efficiency (NUE, g shoot fresh weight/g urea) of Chinese kale grown in (A) loamy sand and (B) clay soils under different nitrogen application rates. Error bars represent standard errors of the mean (n = 5). Different letters above bars within each soil indicate significant differences at $P < 0.05$ according to the Tukey's HSD test. Values are means of two growing seasons (February-March 2024 and 2025).

Stem diameter, shoot fresh weight, shoot dry weight, and root dry weight at 25 DAT were significantly influenced by N application, whereas soil texture affected only shoot fresh weight (Table 4). Loamy sand produced greater shoot fresh weight (8.71 g pot^{-1}) compared with clay (7.79 g pot^{-1}). Nitrogen application markedly increased all growth traits, with maximum values at N4 (0.96 g urea pot^{-1}): stem diameter (7.42 cm), shoot fresh weight (12.41 g pot^{-1}), shoot dry weight (2.45 g pot^{-1}), and root dry weight (0.23 g pot^{-1}), compared with the control (5.50 cm, 5.69 g pot^{-1}, 1.05 g pot^{-1}, and 0.12 g pot^{-1}, respectively). Intermediate N rates improved growth relative to the control but were less effective than N4. These findings confirm that adequate N enhances vegetative growth and biomass accumulation in Brassica and leafy crops (Liu et al., 2014; Muhammad et al., 2024). The soil × N interaction was nonsignificant for shoot and root dry weights, although the greatest values occurred in loamy sand with N4, while the lowest were in clay with N1 (0 g urea pot^{-1}).

The shoot:root ratio also responded to N application, increasing from 8.75 at N1 to 10.05 at N4 (Table 4). Although soil texture showed a nonsignificant effect, loamy sand tended to produce a higher ratio (10.67) than clay (8.00). The soil × N interaction was significant, with the highest shoot:root ratios observed in loamy sand with N4 (9.61), while the lowest ratio occurred in loamy sand with N3 (6.00). These trends indicate that N supply influences biomass partitioning between shoots and roots, with greater allocation toward shoot growth under higher N availability.

The greater shoot fresh weight in loamy sand compared with clay contrasts with Vityakon et al. (1988), who reported higher biomass in clayey soils. The discrepancy is likely due to initial fertility differences: the clay soil in this study had much lower N, P, and K (0.08%, 3.50 mg kg^{-1}, and 60.00 mg kg^{-1}, respectively) than the silty clay loam studied by Vityakon et al. (1988) (0.09%, 13.00 mg kg^{-1}, and 242.00 mg kg^{-1}, respectively).

Correlation analysis of agronomic and physiological traits

Correlation heatmaps (Fig. 1) revealed strong positive associations among biomass traits (shoot and root fresh and dry weights, and stem diameter), particularly in clay soil ($r > 0.90$***), confirming biomass accumulation as the key determinant of yield potential in Chinese kale (Xu et al., 2012). Chlorophyll content was moderately correlated with biomass traits ($r = 0.40$–0.60**), supporting its use as an indicator of N status (Kalaji et al., 2017). In contrast, leaf number was weakly or non-significantly correlated ($r < 0.40$), consistent with previous studies showing that foliage count is not a reliable yield predictor (Treadwell et al., 2007; Khan et al., 2009).

Principal component analysis of growth traits

The PCA biplot (Fig. 2) showed that PC1 (61.9%) was primarily associated with biomass-related traits, including shoot fresh weight, root fresh weight, stem diameter, shoot dry weight, and root dry weight, indicating that these traits collectively drive yield performance. PC2 (14.1%) was mainly influenced by leaf number, which exhibited an opposite trend to root dry weight. Clay soil samples clustered at higher PC1 scores, reflecting greater biomass accumulation, whereas loamy sand samples clustered at lower PC1 scores, consistent with reduced growth under nutrient-limited conditions. These findings are in line with earlier multivariate analyses identifying biomass traits as the main discriminators of soil or nutrient treatments in leafy crops (Moukoumbi et al., 2023; Shukla et al., 2024).

Agronomic nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) responded differently to urea application rates across the two soil types (Fig. 3). In loamy sand, NUE was highest at 0.32 g urea pot^{-1} (5.81 g shoot fresh weight g^{-1} urea), decreased at 0.64 g urea pot^{-1} (2.87), and then

Table 1. Initial soil chemical properties (0–20 cm) of the loamy sand and clay soils used for Chinese kale cultivation.

Parameter	Loamy sand soil	Clay soil
Soil pH (Soil: H_2O, 1: 2.5)	5.85	5.02
Electrical conductivity (dS m^{-1})	0.06	0.17
Soil organic matter (%)	0.10	0.40
Total nitrogen (%)	0.05	0.08
Available phosphorus (mg kg^{-1})	13.00	3.50
Exchangeable potassium (mg kg^{-1})	100.00	60.00

Table 2. Plant height (cm) of Chinese kale as affected by soil textures, nitrogen rates and their interactions. Values are means of two growing seasons (February-March 2024 and 2025).

Treatment	7 DAT	14 DAT	25 DAT
Soil textures (S)			
Loamy sand (S1)	6.21	10.26	14.80 a
Clay (S2)	7.56	9.96	13.20 b
N rate (g urea pot^{-1}) (N)			
0 (N1)	6.54	10.00	12.88 b
0.32 (N2)	6.81	10.16	13.88 b
0.64 (N3)	6.87	9.79	12.93 b
0.96 (N4)	7.33	10.50	16.33 a
S x N			
S1 x N1	5.92	10.17	12.35 c
S1 x N2	6.13	11.13	16.00 ab
S1 x N3	6.15	9.42	14.20 bc
S1 x N4	6.67	10.33	16.67 a
S2 x N1	7.17	9.83	13.42 c
S2 x N2	7.50	9.18	11.75 c
S2 x N3	7.58	10.17	11.67 c
S2 x N4	8.00	10.67	16.00 ab
S	ns	ns	*
N	ns	ns	**
S x N	ns	ns	**
CV (%)	25.31	11.03	6.60

DAT: Days after transplanting.

Different lowercase letters indicate significant differences according to Tukey's HSD test ($P < 0.05$, *; $P < 0.01$, **). ns = not significant ($P > 0.05$).

increased again at 0.96 g urea pot^{-1} (5.63), although these differences were not statistically significant. In clay soil, NUE was lowest at 0.32 g urea pot^{-1} (2.13) and 0.64 g urea pot^{-1} (1.40), but increased substantially at 0.96 g urea pot^{-1} (7.31), which was significantly higher than the two lower urea rates. These results indicate that NUE was optimized at a lower N rate in loamy sand, whereas clay required a higher input to achieve maximum efficiency.

This trend supports the principle that NUE declines under excessive N due to diminishing returns in biomass production (Fageria and Baligar, 2005; Xu et al., 2012). Similar responses have been reported in Brassica vegetables, with sandy soils generally showing higher efficiency at lower N inputs compared with finer-textured soils (Yeshiwas, 2017; Muhammad et al., 2024). NUE was also consistent with differences in chlorophyll content and photosynthetic performance observed between loamy sand and clay soils (Fageria and Baligar, 2005; Netto et al., 2005; Dong et al., 2012). Collectively, these results emphasize the need for soil-specific nutrient management to maximize N efficiency while minimizing environmental losses (Cassman et al., 2003).

Materials and methods

Plant material

Chinese kale (*Brassica oleracea* var. *alboglabra*; Large Leaf, open-pollinated variety) was used in this study. Seeds were sourced from a commercial supplier in Thailand (Chia Tai Co., Ltd.). Seeds were sown in 120-cell plastic trays filled with

Table 3. Chlorophyll (SPAD) content of Chinese kale as affected by soil textures, nitrogen rates and their interactions. Values are means of two growing seasons (February-March 2024 and 2025).

Treatment	14 DAT	25 DAT
Soil textures (S)		
Loamy sand (S1)	48.65	49.25 a
Clay (S2)	47.75	45.34 b
N rate (g urea pot^{-1}) (N)		
0 (N1)	48.82	43.61
0.32 (N2)	49.28	51.16
0.64 (N3)	45.96	40.75
0.96 (N4)	48.73	53.65
S x N		
S1 x N1	48.90	35.78 bc
S1 x N2	48.31	56.23 a
S1 x N3	48.55	49.63 ab
S1 x N4	48.83	55.37a
S2 x N1	48.74	51.45 a
S2 x N2	50.24	46.08 abc
S2 x N3	43.37	31.88 c
S2 x N4	48.63	51.93 a
S	ns	**
N	ns	ns
S x N	ns	*
CV (%)	13.04	19.33

DAT: Days after transplanting.

Different lowercase letters indicate significant differences according to Tukey's HSD test ($P < 0.05$, *; $P < 0.01$, **). ns = not significant ($P > 0.05$).

washed sand and maintained under greenhouse conditions for 10 days. Uniform, healthy seedlings with 3-4 true leaves were selected for transplanting. No chemical treatments were applied to either seeds or seedlings prior to establishment.

Experimental site, soil sampling and analysis

The experiment was conducted in a greenhouse at Mahasarakham University, Maha Sarakham Province, Northeast Thailand, during two consecutive growing seasons (February–March 2024 and February–March 2025). Two contrasting soils were used: loamy sand collected from the University farm (16°20′43″N, 103°12′38″E) and clay collected from a farmer's field in Chiang Yuen District, Maha Sarakham Province (16°22′53″N, 104°9′43″E). Both sites are situated at approximately 150 m above mean sea level. Composite soil samples were collected from the 0–20 cm depth using an auger, air-dried, and passed through a 2-mm sieve prior to use.

Soil physicochemical properties were determined following standard procedures. Soil texture was analyzed using the hydrometer method. Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-water suspension. Soil OM content was quantified using the Walkley and Black wet oxidation method. Total N was analyzed by the micro-Kjeldahl digestion and distillation procedure. Available P was extracted using the Bray II solution, and exchangeable K was extracted with 1 *N* ammonium acetate (NH_4OAc, pH 7.0) and determined using flame photometry. All analytical methods followed Jones (2001).

Experimental design and treatments

The experiment was arranged in a 2 × 4 factorial completely randomized design (CRD) with five replications. The first factor was soil texture: loamy sand (S1) and clay (S2). The second factor was nitrogen (N) application rate, supplied as urea (46% N) at 0 (N1), 0.32 (N2), 0.64 (N3), and 0.96 (N4) g pot^{-1}, equivalent to 0, 62.5, 125.0, and 187.5 kg ha^{-1}, respectively.

Farmyard manure was incorporated into all treatments at 144.2 g pot^{-1} (28.13 t ha^{-1}) seven days before transplanting. A compound fertilizer (15–15–15) was applied as a basal dose at 1.60 g pot^{-1} (312.5 kg ha^{-1}) three days after transplanting. Urea was top-dressed according to treatment levels at 10 days after transplanting.

Table 4. Stem diameter, biomass traits, and shoot:root ratio of Chinese kale at harvest as affected by soil textures, nitrogen rates and their interactions. Values are means of two growing seasons (February-March 2024 and 2025).

Treatment	Stem diameter (cm)	Shoot fresh weight (g pot^{-1})	Shoot dry weight (g pot^{-1})	Root dry weight (g pot^{-1})	Shoot:root ratio
Soil textures (S)					
Loamy sand (S1)	6.42	8.71	1.60	0.15	10.67
Clay (S2)	5.49	7.79	1.44	0.18	8.00
N rate (g urea pot^{-1}) (N)					
0 (N1)	5.50 b	5.69 c	1.05	0.12 b	8.75
0.32 (N2)	5.62 b	7.63 b	1.41	0.15 b	9.40
0.64 (N3)	5.90 b	7.46 b	1.36	0.15 b	9.07
0.96 (N4)	7.42 a	12.41 a	2.01	0.20 a	10.05
S x N					
S1 x N1	5.32	6.05b	0.94	0.14 b	6.71
S1 x N2	5.60	7.66b	1.36	0.19 b	7.16
S1 x N3	6.17	7.38b	1.08	0.18 b	6.00
S1 x N4	7.13	9.50ab	2.00	0.23 ab	9.61
S2 x N1	4.99	4.58c	0.91	0.14 b	6.50
S2 x N2	5.26	6.82b	1.22	0.15 b	8.13
S2 x N3	4.90	6.38b	1.32	0.16 b	8.25
S2 x N4	7.02	12.61a	2.04	0.27 a	7.56
S	ns	ns	ns	ns	**
N	*	*	ns	**	ns
S x N	*	*	ns	*	ns
CV (%)	13.36	28.82	35.50	22.66	23.13

Different lowercase letters indicate significant differences according to Tukey's HSD test ($P < 0.05$, *; $P < 0.01$, **). ns = not significant ($P > 0.05$).

Crop management

Plastic pots were filled with 10 kg of air-dried soil (loamy sand or clay) passed through a 2-mm sieve. One healthy 10-day-old Chinese kale seedling was transplanted per pot. Soil moisture was maintained at field capacity through regular watering, and weeds were controlled manually. No pesticides were applied during the cropping period. Both experimental seasons were conducted under greenhouse conditions at Mahasarakham University.

Data collection

Plant height and number of leaves were recorded at 7, 14, and 25 days after transplanting (DAT). Chlorophyll (SPAD) content, measured on the third to fourth fully expanded leaf from the apex, was assessed at 14 and 25 DAT. At harvest (25 DAT), stem diameter, shoot fresh weight, root fresh weight, shoot dry weight, and root dry weight were measured. Shoots and roots were oven-dried at 40 °C until constant weight, and the shoot:root ratio was calculated from the corresponding dry weights.

Agronomic nitrogen use efficiency (NUE)

Agronomic NUE was calculated following Fageria and Baligar (2005):

$$\mathrm{NUE} = \frac{\mathrm{Tf\text{-}Tu}}{\mathrm{Nna}}$$

where Tf is the shoot fresh weight of fertilized pots (g), Tu is the shoot fresh weight of unfertilized pots (g), and Nna is the amount of urea fertilizer applied (g pot^{-1}).

Statistical and multivariate analyses

Data were subjected to analysis of variance (ANOVA) using Statistix 10 (Analytical Software, Tallahassee, FL, USA, 2013) according to a 2 × 4 factorial completely randomized design (CRD) with five replications. Treatment means were compared using Tukey's HSD test at the 0.05 and 0.01 probability levels.

Temporal changes in chlorophyll (SPAD) content between 14 and 25 DAT were evaluated using a paired t-test, as both measurements were taken from the same plants.

Trait relationships were assessed using Pearson's correlation analysis among agronomic and physiological parameters. Principal component analysis (PCA) was performed on standardized (z-score) data for chlorophyll content, leaf number, stem diameter, shoot and root fresh weight, and shoot and root dry weight. The first two principal components were retained for interpretation and to generate biplots (Jolliffe and Cadima, 2016; R Core Team, 2023).

Conclusions

This study demonstrated that nitrogen (N) management in Chinese kale (*Brassica oleracea* var. *alboglabra*) is strongly influenced by soil texture. Clay soil supported greater biomass production, whereas loamy sand resulted in comparatively higher shoot fresh weight, reflecting differences in nutrient retention and soil fertility. Increasing urea application enhanced chlorophyll content and plant growth, with the highest values observed at 0.96 g urea pot^{-1}. Multivariate analysis further indicated that biomass-related traits were the primary contributors to yield variation, while leaf number acted as a secondary trait differentiating soil types. Nitrogen use efficiency (NUE) was maximized at a lower urea rate (0.32 g pot^{-1}) in loamy sand, but required a higher rate (0.96 g pot^{-1}) in clay, underscoring the need for soil-specific nutrient management strategies. Biomass traits can therefore be regarded as reliable indicators of yield potential, and targeted N management represents a practical approach for improving Chinese kale production in tropical soils.

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Statement of contributions
BK: Experimental design, manuscript preparation, Conceptualization and overall guidance, and project coordination. TS: Data collection and analysis. SS: Methodology and statistical evaluation. RP: Data interpretation. WP: Laboratory supervision. TVD: Mmanuscript revision. PV: Resources and manuscript revision.

Conflict of Interest
The authors declare that there is no conflict of interest.

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