

Macronutrient content in kale leaves at different times with the use of organic fertilizers

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Abstract: An essential aspect of fertilizer recommendations is the replacement of nutrients extracted by plants and removed through harvest. Crops such as kale (*Brassica oleracea* L. var. *acephala*) exhibit indeterminate growth and are subjected to multiple harvests over an extended production cycle. Consequently, nutrient concentrations in harvested leaves may vary over time, potentially affecting the accuracy of nutrient uptake and export estimates used for fertilizer recommendations. This study aimed to evaluate the dynamics of macronutrient concentrations in kale leaves throughout the production cycle under different organic topdressing fertilizers. The experiment was conducted using a 3 × 5 factorial arrangement in a split-plot design with nine replications. The plots consisted of three topdressing treatments: castor bean cake, bokashi, and a control without topdressing fertilization. The subplots corresponded to five evaluation periods: 64, 92, 120, 148, and 176 days after transplanting (DAT). Fertilizer rates were adjusted to supply 40 kg ha⁻¹ of nitrogen. Leaf concentrations of N, P, K, Ca, Mg, and S were determined throughout the crop cycle. Castor bean cake promoted higher concentrations of N, Mg, and S compared with the other treatments. The average order of nutrient concentration was K > N > Ca > S > P > Mg. All nutrients showed significant quadratic responses over time, with estimated maximum concentrations occurring between 100 and 120 DAT, followed by marked declines. By the end of the crop cycle, reductions relative to peak concentrations reached up to 44% for N, 42% for P, 54% for K, 11% for Ca, 25% for Mg, and 45% for S. These results indicate that leaf sampling performed only at the end of the crop cycle may underestimate nutrient export and compromise soil fertility management and fertilizer recommendation programs.

Keywords: *Brassica oleracea* L. var. *acephala*; Sustainable agriculture; Castor bean cake; Bokashi; Nutrient uptake.

Abbreviations: B= bokashi, CBC (castor bean cake), CWTF= (control without topdressing fertilization), DAT= days after transplanting, (N) = nitrogen, (P) = phosphorus, (K) = potassium, (Ca) = calcium, (Mg) = magnesium, (S)= sulfur.

Introduction

Leaf kale (*Brassica oleracea* L. var. *acephala*), belonging to the family Brassicaceae, has shown a significant increase in consumption over recent decades, driven by shifts in dietary habits and the growing recognition of its nutraceutical value (Ramirez et al., 2020; Bell et al., 2023; Alves et al., 2026). The species is a relevant source of dietary fiber, minerals calcium, phosphorus, magnesium, manganese, and potassium, vitamins A, C, and B-complex, as well as phenolic compounds and organosulfur compounds with well-established biological activity (Satheesh et al., 2020; Alves et al., 2026).

The growing interest in sustainable production systems has driven the adoption of organic farming, in which fertilization plays a central role in maintaining soil fertility and supplying essential elements for plant growth and development. Organic fertilizers, beyond their role as nutrient sources, promote improvements in the physical, chemical, and biological properties of the soil, increasing cation exchange capacity (CEC) and organic matter content (Luís et al., 2023; Alves et al., 2023; Oliveira et al., 2024). However, nutrient availability from these sources is governed by the mineralization kinetics of organic matter, resulting in gradual release and a more prolonged residual effect compared to mineral fertilizers (Alves et al., 2023; Alves et al., 2025a).

Among the most widely used organic fertilizers in vegetable production, castor bean cake stands out for its high nitrogen content and the presence of phosphorus, potassium, and micronutrients (Alves et al., 2025a), while bokashi, a fermented compound produced by efficient microorganisms applied to organic substrates such as straw, manure, and bran, promotes accelerated decomposition of organic matter and the release of nutrients in soluble forms readily available for plant uptake (Álvarez-Solís et al., 2016). The agronomic efficiency of these materials is associated with a carbon-to-nitrogen ratio (C/N) below 30:1, a strategy that has proven effective in ensuring adequate nitrogen availability throughout the growing cycle (Alves et al., 2024; Alves et al., 2025).

Nitrogen is the nutrient required in the greatest quantities by kale and is highly susceptible to leaching losses, so, split applications both at planting and as topdressing throughout the cycle are recommended (Colombari et al., 2018; Alves et al., 2025b). Plant mineral nutrition is a dynamic process in which nutrient demand varies according to the developmental stage and the metabolic reactions associated with each phenological phase (Hawkesford et al., 2012).

Proper management of organic fertilizers considering dose, application timing, and splitting is essential to synchronize nutrient availability with crop demand and to optimize uptake during periods of peak nutritional requirement. Nevertheless, studies on organic fertilization and nutrient uptake dynamics in kale remain scarce, limiting the development of technically sound fertilization recommendations for this crop.

In indeterminate-growth species such as kale, which are subjected to successive harvests throughout the production cycle, the macronutrient content of leaves may change in response to the metabolic demand at each phenological phase and to the mineralization kinetics of the organic fertilizers applied. Fertilizers with distinct characteristics, such as castor bean cake and bokashi, may result in differentiated patterns of nutrient supply, with direct effects on the foliar nutritional profile at each developmental stage, thereby compromising the accuracy of nutrient extraction and exportation estimates and, consequently, fertilization recommendations.

In light of the foregoing, this study aimed to evaluate the macronutrient content in kale leaves throughout the production cycle in an experiment conducted with organic fertilizers applied as topdressing, assessing whether the type of fertilizer influences the foliar nutritional profile at different stages of crop development.

Results

According to the analysis of variance for the nutrients calcium and magnesium, there was no interaction between the factors fertilizers and harvest dates (Table 1). However, the factors were significant individually according to the F-test. When the effect of the fertilizers was significant, separate regressions were fitted for each type of fertilizer. In the absence of a significant fertilizer effect, a single regression was used, combining both treatments.

Table 1. Analysis of variance for the levels of macronutrients nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) as a function of organic fertilizers, castor bean cake, bokashi applied as topdressing and the control without topdressing fertilization at different harvest dates.

Source of Variation	N	P	K	Ca	Mg	S
Values of mean square						
Fertilizers	670.74**	19.38**	1424.82**	179.17**	2.65**	172.97**
Residual	6.47	0.44	5.93	1.48	0.06	0.62
Evaluation times	710.89**	27.62**	2374.17**	12.47**	1.00**	117.93**
Fertilizers X Evaluation times	23.51**	0.92*	20.38*	1.99 ^{ns}	0.03 ^{ns}	18.17**
Residual	5.58	0.31	8.90	1.09	0.05	0.98
CV(%) Plots	9.91	11.61	7.16	7.27	7.39	8.54
CV (%) Subplots	10.67	10.36	8.77	6.26	6.83	10.75

CV = Coefficient of Variation; *, **, ^{ns} = significant at 5%, 1%, and not significant by the F-test, respectively.

There was a significant difference among the fertilizer sources. For calcium, no differences were observed among the topdressing sources; however, all treatments promoted higher levels compared to the control (Table 2). Regarding magnesium, in comparison among sources, the application of bokashi resulted in the highest nutrient levels (Table 2).

Table 2. Mean contents of macronutrients calcium (Ca) and magnesium (Mg) as affected by the organic fertilizers castor bean cake and bokashi applied as topdressing.

	Ca	Mg
g kg ⁻¹ of dry matter		
Castor bean cake	17.84 a	3.48 b
Bokashi	17.91 a	3.67 a
Control without topdressing fertilization	14.42 b	3.18 c

Means followed by the same letter in the columns (Tukey's test) do not differ significantly at the 5% probability level.

In the comparison among topdressing treatments, for nitrogen, phosphorus, potassium, and sulfur contents, the fertilizers castor bean cake and bokashi did not differ from each other across the evaluation times, differing only from the control treatment without topdressing. However, for nitrogen content at 90 DAT, the application of castor bean cake resulted in higher values, reaching 30 g kg⁻¹ of dry matter. In contrast, for sulfur at 62 DAT, bokashi did not differ from the control treatment (Table 3).

Table 3. Mean contents of macronutrients nitrogen (N), phosphorus (P), potassium (K) and sulfur (S) as affected by the organic fertilizers castor bean cake and bokashi applied as topdressing and the control without topdressing fertilization.

	62	90	120	148	176
Nitrogen g kg⁻¹ of dry matter					
Castor bean cake	22.11 a	30.00 a	31.55 a	32.00 a	19.66 a
Bokashi	20.77 a	25.88 b	29.22 a	31.33 a	17.22 a
Control without topdressing fertilization	17.66 b	18.37 c	24.11 b	23.33 b	14.33 b
Phosphorus g kg⁻¹ of dry matter					
Castor bean cake	5.82 a	6.94 a	6.75 a	6.65 a	4.44 a
Bokashi	5.73 a	7.17 a	6.78 a	6.52 a	4.12 a
Control without topdressing fertilization	5.30 b	5.16 b	5.56 b	5.33 b	3.43 b
Potassium g kg⁻¹ of dry matter					
Castor bean cake	40.89 a	44.11 a	45.88 a	35.77 a	21.00 a
Bokashi	40.11 a	45.44 a	43.66 a	33.88 a	21.67 a
Control without topdressing fertilization	30.33 b	35.44 b	34.31 b	22.33 b	15.00 b
Sulfur g kg⁻¹ of dry matter					
Castor bean cake	11.40 a	11.45 a	11.33 a	11.78 a	7.35 a
Bokashi	10.35 ab	11.41 a	11.38 a	10.75 a	6.33 a
Control without topdressing fertilization	10.08 b	10.18 b	6.43 b	4.78 b	3.56 b

Means followed by the same letter in the columns (Tukey's test) do not differ significantly at the 5% probability level.

Regression analysis showed that the quadratic model provided the best fit for the contents of all macronutrients evaluated, except for sulfur in the treatment without topdressing (Fig.1). For nitrogen, the maximum estimated content was 30.75 g kg⁻¹ DM at 120 DAT for the bokashi treatment, 32.79 g kg⁻¹ DM at 118 DAT for castor bean cake, and 23.71 g kg⁻¹ DM at 121 DAT for the control without topdressing fertilization (Fig.1A). Compared to the first evaluation at 64 DAT, nitrogen content increased by 48% for both organic fertilizers and by 33% for control without topdressing fertilization. Conversely, at the final harvest (176 DAT), reductions of 44%, 40%, and 39% were observed for bokashi, castor bean cake, and the control without topdressing fertilization, respectively.

For phosphorus, the maximum leaf concentrations were 7.09 g kg⁻¹ DM at 111 days after transplanting (DAT) under bokashi application, 7.07 g kg⁻¹ DM at 108 DAT for castor bean cake, and 5.33 g kg⁻¹ DM at 94 DAT for control without topdressing fertilization. Compared to the initial sampling (64 DAT), the contents of this macronutrient increased by 22% and 23% for bokashi and castor bean cake, respectively, whereas the control without topdressing fertilization remained virtually stable, with a variation under 1%. Subsequently, at the final harvest (176 DAT), there was a reduction of 37% (bokashi), 42% (castor bean cake), and 36% (without topdressing fertilization) compared to their respective maximum estimated contents.

The maximum potassium contents calculated for the treatments with bokashi, castor bean cake, and control without topdressing fertilization were 45.25, 45.67, and 34.05 g kg⁻¹ of dry matter, reached at 98, 99, and 95 (DAT), respectively. Compared with the first evaluation (64 DAT), the observed increases were 12.8% for bokashi, 11.7% for castor bean cake, and 12.3% for the treatment without topdressing fertilization. After reaching the maximum values, potassium contents decreased until the end of the cycle (176 DAT), with reductions of 52.1%, 54.0%, and 55.9% for bokashi, castor bean cake, and control without topdressing fertilization, respectively.

The maximum calculated calcium contents were obtained at 111, 133, and 99 days after transplanting (DAT), with calculated values of 18.26, 19.56, and 14.75 g kg⁻¹ DM for the bokashi, castor bean cake, and control without topdressing fertilization treatments, respectively (Figure 1D). These values represented increases of 8%, 12%, and 4.5%, respectively, compared to the initial evaluation at 64 DAT. However, at the end of the evaluation cycle (176 DAT), reductions of 6%, 11%, and 12%, respectively, were observed in the calcium contents under bokashi, castor bean cake, and control without topdressing fertilization treatments, respectively.

For magnesium, the maximum contents were reached at 120, 148, and 107 DAT, with values of 4.43, 3.83, and 3.34 g kg⁻¹ DM for the bokashi, castor bean cake, and no topdressing fertilization treatments, respectively (Fig.1E). Compared to the initial evaluation performed at 64 DAT, these values corresponded to increases of 23%, 11%, and 4%, respectively. However, by the end of the evaluation cycle (176 DAT), reductions of 25%, 17%, and 13% were observed in the magnesium contents of the bokashi, castor bean cake, and no topdressing fertilization treatments, respectively.

Regarding sulfur, the estimated maximum contents were 11.88 and 11.45 g kg⁻¹ of dry matter at 100 and 101 DAT in the treatments with bokashi and castor bean cake application, respectively (Fig. 1F). Compared with the first evaluation, performed at 64 DAT, increases of 11% for bokashi and 5% for castor bean cake were observed. By the end of the cycle (176 DAT), reductions of 45% and 38% were observed, respectively. For the treatment without topdressing fertilization, the best fit obtained was a decreasing linear model, with a maximum content of 10.06 g kg⁻¹ of dry matter at 64 DAT and a reduction of 64% throughout the cycle.

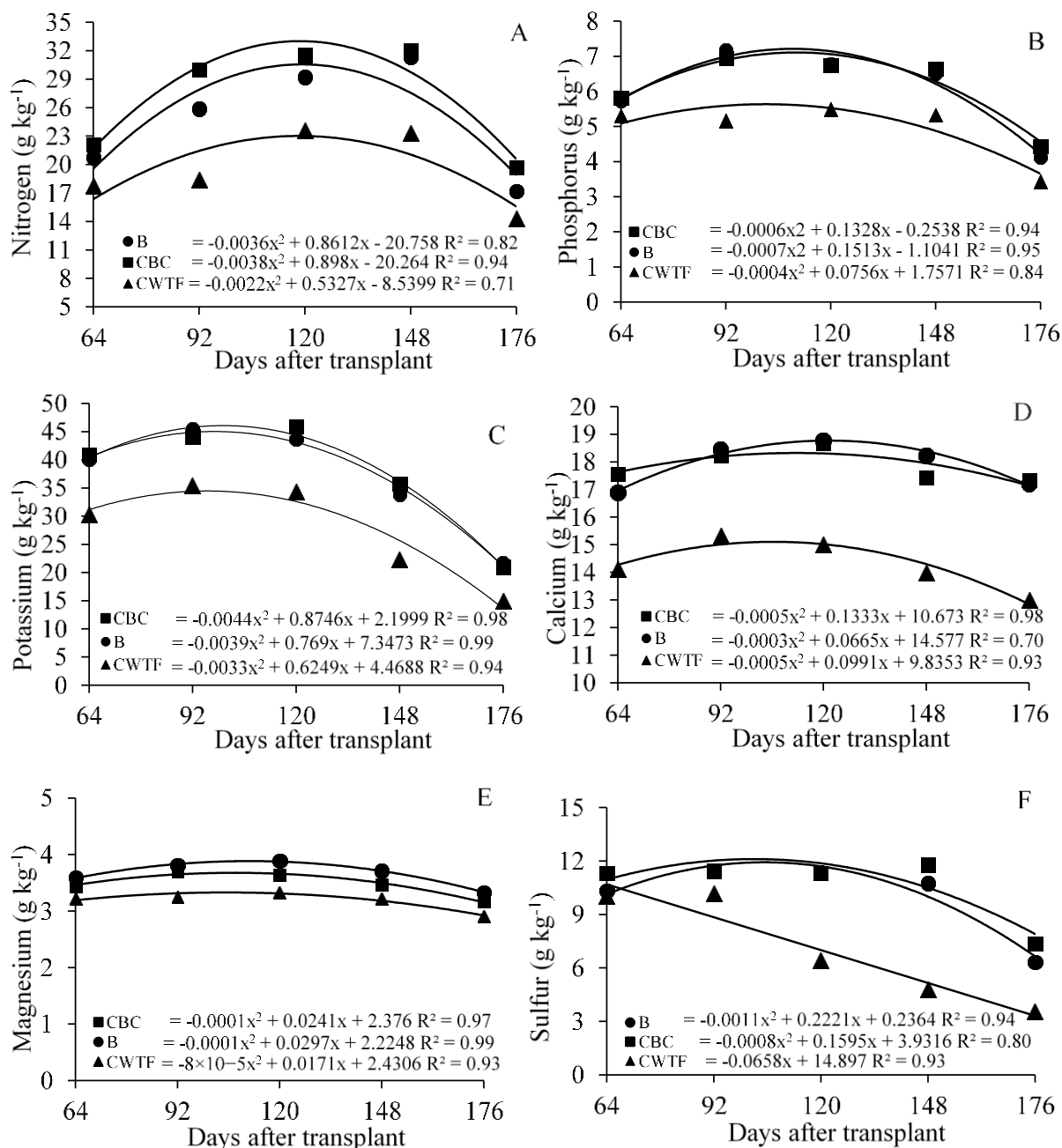


Figure 1. Nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E), and sulfur (F) content in plants fertilized with the organic fertilizers castor bean cake, bokashi applied as topdressing and and control without topdressing fertilization across different harvest dates.

Discussion

Plant nutrition is a fundamental pillar for the healthy development and productivity of agricultural crops. Among the various essential elements, the macronutrients nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur play crucial roles in physiological and biochemical processes of plants. The adequate availability of these nutrients in the soil, and their subsequent absorption by plants, is decisive for vegetative growth, biomass formation, and the final quality of the product. In the context of sustainable agriculture, the use of organic fertilizers has gained prominence as an alternative to synthetic inputs, promoting soil health and nutrient cycling.

The results showed that treatments with castor bean cake and bokashi promoted significantly higher contents of N, P, K, Ca, Mg, and S compared to the treatment without topdressing fertilization (Tables 2 and 3), regardless of the sampling date. Notably, for nitrogen, despite being applied in equal amounts, castor bean cake resulted in a higher concentration (30 g kg^{-1}) at 90 DAT. These differences in nutrient availability, especially considering that the release of organic fertilizers is not immediate, are attributed to variations in the mineralization rates and composition of the materials. Nordi et al. (2022) observed a higher accumulation of most macronutrients (except Ca and S) in the shoot of *Acmella oleracea* (jambu) plants when using castor bean cake compared to bokashi, correlating this effect with the faster nutrient release from castor bean cake.

Despite the similarity in C/N ratios between castor bean cake (10:1) and bokashi (11:1), the explanation for the greater efficiency of castor bean cake in nutrient release transcends this isolated metric. Factors such as the intrinsic composition of the material, physical structure, the presence of easily degradable compounds, and specific microbial activity can significantly influence the mineralization rate. Studies by Silva et al. (2016a, 2018b) demonstrated higher yield and dry matter accumulation in beet with castor bean cake. Almeida et al. (2021) highlighted castor bean cake as more efficient in releasing nitrogen and other nutrients, surpassed only by hoof and horn meal. Severino et al. (2005) emphasize the high microbial activity and rapid decomposition of castor bean cake, which accelerates nutrient release and absorption by plants. Souza et al. (2023) corroborate that castor bean cake provides more efficient nutrient release compared to bokashi.

It is crucial to highlight the dominant role of the organic compost Provaso® at the base, applied at a rate of 30 t ha⁻¹. This provided a substantial amount of nutrients, including 105 kg ha⁻¹ of N, 138 kg ha⁻¹ of P₂O₅, 201 kg ha⁻¹ of K₂O, and 483 kg ha⁻¹ of Ca. The significant contribution of these nutrients at the base, prior to the application of topdressing fertilizers, establishes a high nutritional baseline that can influence the plant response to subsequent treatments and the nutrient release dynamics of organic topdressing fertilizers.

Several studies confirm the benefits of castor bean cake as a topdressing, resulting in dry matter increases in crops such as zucchini (*Cucurbita pepo*) (Lanna et al., 2020), beet (*Beta vulgaris*) (Silva et al., 2016a), chives (*Allium schoenoprasum*) (Oliveira et al., 2024), kale (*Brassica oleracea* var. *acephala*) (Alves et al., 2025b), cauliflower (*Brassica oleracea* var. *botrytis*) (Candian et al., 2024), jambu (*Acmella oleracea*) (Nordi et al., 2022; Alves et al., 2023; Alves et al., 2025a), cabbage (*Brassica oleracea* var. *capitata*) (Cardoso et al., 2020; Hounmenou et al., 2021), and parsley (*Petroselinum crispum*) (Luis et al., 2023). This wide applicability makes it one of the preferred nitrogen sources in organic topdressing systems (Almeida et al., 2021; Nordi et al., 2022).

For all macronutrients, the content data throughout the crop cycle fit a quadratic model, characterized by increasing contents up to a maximum point, followed by a decline towards the end of the harvest period. This dynamic is intrinsically linked to the vegetative growth of the crop, which demands greater nutrient uptake during the intermediate stages of the cycle, followed by nutrient redistribution or dilution in the final phase, as described by Taiz et al. (2024).

The maximum nitrogen contents remained within the adequate range for kale cultivation (30 to 55 g kg⁻¹ of dry matter), according to the parameters established by Trani et al. (2015). Phosphorus and potassium contents exceeded the values considered adequate (3 to 7 g kg⁻¹ DM for P and up to 40 g kg⁻¹ DM for K), while calcium and magnesium contents remained within acceptable limits (maximums of 25 g kg⁻¹ DM and 7 g kg⁻¹ DM, respectively).

Both organic fertilizers, castor bean cake and bokashi, provided adequate nutrient contents to meet the crop's nutritional requirements, resulting in superior performance compared to the treatment without topdressing fertilization. Nasser et al. (2020) analyzed nutrients in 'Hi Crop' kale leaves and reported values of 37.9, 36.5, 21.7, 4.5, 4.2, and 3.8 g kg⁻¹ DM for K, N, Ca, Mg, S, and P, respectively. It is important to note that the values for N, Ca, and Mg reported by Nasser et al. (2020) at 60 DAT were higher than those found in this study.

The increasing number of new leaves (sinks) over the harvest weeks may have intensified competition for photoassimilates and nutrients, leading to a decrease in macronutrient content in the leaves over time due to intraspecific competition. Additionally, continuous nutrient uptake by both cultivated and spontaneous plants, as well as nutrient leaching or fixation, may have contributed to reduced nutrient availability in the soil. In bush zucchini, Araújo et al. (2015) observed a decline in content of most macronutrients throughout the cycle, attributing this reduction to the increasing number of harvested fruits and the extraction of soil nutrients.

Accurate determination of nutrient content is crucial for calculating extraction and export by plants. To prevent the exhaustion of nutrient availability in the soil for subsequent crops, at a minimum, the extracted amount must be replenished, also considering losses due to leaching, fixation, and other factors. The common practice of performing only a single leaf sampling at the end of the cycle to determine nutrient content and calculate extraction can significantly underestimate the actual values. For some nutrients, the difference between the content at the end of the cycle and at its peak can exceed 100%, resulting in an estimate up to 50% lower than the maximum. In situations where continuous analysis is not feasible, it is recommended to collect leaf samples at multiple harvests, combine them proportionally to the biomass harvested at each point, and analyze this "composite" sample for a more accurate estimate of nutrient extraction by kale leaves throughout the cycle.

The decreasing order of macronutrient content in kale leaves across all harvests was K > N > Ca > S > P > Mg, confirming the high extraction of K and N. Nasser et al. (2020) observed a similar trend: K > N > Ca > Mg > S > P. The increase in foliar nitrogen is vital for vegetative growth and biomass production, being a structural component of proteins, enzymes, and chlorophyll (Taiz et al., 2024).

Nitrogen is one of the most important macronutrients for plant growth, being an essential component of proteins, nucleic acids (DNA and RNA), phospholipids, chlorophyll, hormones, and vitamins (Nordi et al., 2022; Wang et al., 2024; Alves et al., 2026). Its presence is vital for photosynthesis and biomass formation, being a limiting factor for plant growth and development (Nordi et al., 2022). The increase in foliar nitrogen is directly correlated with vegetative growth and crop productivity (Nordi et al., 2022; Taiz et al., 2024).

Phosphorus plays a crucial role in energy storage and transfer in plants, being a fundamental component of ATP (adenosine triphosphate) and ADP (adenosine diphosphate). It is essential for processes such as photosynthesis, respiration, cell division, and development (Carvalho et al., 2025; Alves et al., 2026). Phosphorus deficiency can result in stunted growth and purplish discoloration of leaves (Taiz et al., 2024).

Potassium absorption by plants occurs mainly through mass flow and diffusion, being a highly mobile nutrient both in the soil and within the plant. K^+ is rapidly absorbed by roots and redistributed via phloem to developing organs (Nordi et al., 2022). As an essential cation for osmotic regulation, potassium is central to stomatal opening and closing, influencing transpiration and photosynthesis (Sardans et al., 2021; Taiz et al., 2024). Furthermore, it activates enzymes in carbohydrate metabolism and protein synthesis, being fundamental for vegetative growth and leaf quality (Nasser et al., 2020).

Calcium is an essential macronutrient for plant growth and development, playing a fundamental role in the formation and stability of cell walls through the formation of calcium pectates. In leafy vegetables, such as kale, this nutrient directly contributes to maintaining structural integrity, tissue firmness, and post-harvest quality of the leaves. In addition to its structural function, calcium participates in maintaining cell membrane integrity, cell division and expansion, and signaling processes involved in plant physiological responses to different environmental conditions. Due to its low mobility in the phloem, a continuous supply of calcium is necessary to meet the demand of young growing tissues, and deficiency symptoms commonly appear first in these regions. Thus, adequate calcium availability is indispensable to ensure vegetative development, productivity, and commercial quality of kale cultivation (Rengel et al., 2022; Taiz et al., 2024).

Magnesium is crucial for photosynthesis, being the central atom of the chlorophyll molecule, the pigment responsible for capturing light energy. Additionally, it acts as an enzymatic cofactor in various metabolic reactions, including protein and carbohydrate synthesis. Its higher content may have contributed to plant development with castor bean cake (Marschner, 2012). Sulfur is linked to the synthesis of sulfur-containing amino acids (cysteine and methionine), which are building blocks of proteins. It is also a component of vitamins and secondary plant defense compounds, such as glucosinolates, which confer resistance to pests and diseases (Epstein & Bloom, 2006). Thus, the increase in S in leaves with castor bean cake reinforces its role as a nutrient source and a potential inducer of resistance, improving overall crop performance.

Materials and methods

Location of the experimental area

The experiment was conducted at the Experimental Farm of São Manuel (22° 44'28" S and 48° 34'37" WGr and altitude of 740 m), School of Agricultural Sciences (FCA) - São Paulo State University (UNESP). The region's climate, according to the Köppen classification, is mesothermal type Cfa, humid subtropical, with rainy summers and dry winters (Franco et al., 2023).

The soil in the area is classified as Typical Dystrophic Red Latosol and the crop that preceded the implementation of the experiment was corn. Before the installation of the experiment, soil was collected (0-20 cm) for chemical analysis, obtaining the following values: $pH_{(CaCl_2)} = 5.8$, organic matter = 13 g dm⁻³, $P_{resin} = 190$ mg dm⁻³, base saturation (V) = 67%, H + Al = 11 mmol_c dm⁻³, K = 3.5 mmol_c dm⁻³, Ca = 12 mmol_c dm⁻³, Mg = 7 mmol_c dm⁻³, SB = 22 mmol_c dm⁻³, CEC = 33 mmol_c dm⁻³, S = 5 mg dm⁻³, B = 0.22 mg dm⁻³, Cu = 2.0 mg dm⁻³, Fe = 47 mg dm⁻³, Mn = 5.8 mg dm⁻³ and Zn = 18.2 mg dm⁻³.

Treatments, conduction of study and experimental design

Ten treatments were evaluated in a 3 × 5 factorial arrangement in a split-plot scheme, in which the plots consisted of the topdressing treatments (castor bean cake, bokashi, and control with topdressing fertilization), and the subplots corresponded to the evaluation intervals (64, 92, 120, 148, and 176 days after transplanting — DAT). The experimental design was a randomized complete block with nine replications of 18 plants per plot.

Prior to transplanting, organic compost Provaso® was applied at a rate of 30 t ha⁻¹ and incorporated into the entire experimental area (Trani et al., 2013). Chemical characterization was performed for all organic fertilizers used in the experiment (Table 4). Topdressing applications were carried out at 21-day intervals throughout the crop cycle, representing the standard management practice adopted for both fertilizers. It is important to note that the application interval was not an experimental factor, but rather a fixed management condition common to both treatments, designed to ensure equivalent and regularly distributed nitrogen supply across the cycle. At each application, a dose equivalent to 40 kg ha⁻¹ of N was applied in the respective treatments, so that both castor bean cake and bokashi provided the same cumulative nitrogen input, differing only in the organic source and its associated mineralization kinetics.

In this study it was used the same field experiment as Alves et al. (2025), but reports previously unpublished leaf macronutrient contents dynamics and implications for nutrient export estimation.

The hybrid Hi-Crop (Takii) was used, and sowing was carried out in polypropylene trays with 162 cells, containing Carolina® substrate, with one plant per cell. The seedlings were transplanted into beds with spacing of 0.50 m between rows and 1.00 m between plants, totaling 18 plants per plot (3 rows with 6 plants each), but only the four central plants of each plot were evaluated. The implantation and the cultural management followed the technical recommendations, according to Trani et al. (2013) and Filgueira (2008) and the irrigation system used was sprinkler, applying an average of 3 mm of water per day.

Characteristics evaluated

Harvests were carried out every seven days, starting at 50 days after transplanting (DAT), with the final harvest occurring at 176 DAT. Leaves were harvested when they reached between 20 and 30 cm in length, and only commercially acceptable leaves free from visible defects were selected for evaluation. On specific dates (64, 92, 120, 148, and 176 DAT), the leaves were washed, placed in paper bags, and dried in a forced-air oven at 65 °C for 72 hours to determine dry mass. The dried material was then ground using a Wiley mill and digested for analysis of N, P, K, Ca, Mg, and S contents.

Table 4. Chemical characteristics of the organic fertilizers used and estimated quantity of nutrients applied. FCA/UNESP, São Manuel-SP

	Provaso®	Castor bean cake	Bokashi
	% (natural)		
N	0.35	4.34	2.39
P ₂ O ₅	0.46	1.22	2.00
K ₂ O	0.67	1.09	1.58
Ca	1.61	1.12	5.21
Mg	0.29	0.60	0.56
S	0.3	0.32	0.48
Moisture	36	7	7
Organic matter	19	76	47
Relation C/N	10/1	10/1	11/1
pH	8.2	6.3	7.9
	30 t ha ⁻¹ of compost	40 kg ha ⁻¹ (N) in topdressing	40 kg ha ⁻¹ (N) in topdressing
	(Values in kg ha ⁻¹ of compost before planting)		
N	105	921.66	1673.6
P ₂ O ₅	138	224.48	669.6
K ₂ O	201	200.56	529.0
Ca	483	206.08	1673.6
Mg	87	110.4	187.5
S	90	58.88	160.7

The N content in the leaves was determined by sulfuric acid digestion and quantified using the semi-micro-Kjeldahl method. P, K, Ca, Mg, and S contents were determined by atomic absorption spectrophotometry after nitric-perchloric digestion method, following the methods described by Malavolta, Vitti, and Oliveira (1997).

Statistical analysis

The data were subjected to the Shapiro–Wilk test for normality and Bartlett's test for homogeneity of variances. After verification of these assumptions, analysis of variance was performed for a split-plot factorial arrangement, in which topdressing fertilization treatments were allocated to the main plots and evaluation periods to the subplots. When significant, treatment means were compared using Tukey's test at the 5% probability level ($p \leq 0.05$), while the effect of evaluation periods was assessed by polynomial regression analysis. All statistical analyses were performed using SISVAR software (Ferreira, 2014).

Conclusion

Castor bean cake promoted higher foliar contents of N, Mg, and S in kale compared to bokashi, reflecting differences in mineralization kinetics between the two organic sources. The temporal dynamics of all macronutrients followed a quadratic pattern throughout the production cycle, consistent with nutrient dilution by biomass accumulation and remobilization from senescent tissues, with the macronutrient ranking $K > N > Ca > S > P > Mg$ observed across all harvests. These findings demonstrate that single-point sampling is insufficient to capture the temporal variability of nutrient accumulation in indeterminate-growth species such as kale, and that stage-specific topdressing programs calibrated to the quadratic accumulation pattern are essential for optimizing nutrient use efficiency in organically managed crops.

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