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CROP PRODUCTION

# Optimizing *Merremia aegyptia* and *Calotropis procera* biomass application rates in kale cultivation under semi-arid conditions

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**ABSTRACT.** This study aimed to optimize both agronomically and economically leaf green mass productivity of kale and its agronomic components when fertilized with equivalent biomass amounts of the hairy woodrose (*Merremia aegyptia* L.) and roostertree (*Calotropis procera* Ait.) spontaneous species from the Caatinga biome in two cropping seasons. The experimental design was in randomized blocks with five treatments and five replications. The treatments consisted of equivalent biomass amounts of hairy woodrose and roostertree at doses of 16, 29, 42, 55, and 68 ton ha$^{-1}$, on a dry basis. In each experiment, a treatment without fertilization (control) and a treatment with chemical fertilization were used. The maximum optimized physical efficiencies of the kale commercial leaf productivity and number of leaf packets per square meter were 16.92 ton ha$^{-1}$ and 6.97, respectively, when the amounts of the green manure biomass of 56.41 and 48.63 ton ha$^{-1}$ were incorporated into the soil. The optimized maximum net income of 47,841.44 BRL ha$^{-1}$ and rate of return of 2.47 reals for each real invested were obtained when the amounts of the green manure biomass were 53.26 and 64.31 ton ha$^{-1}$ added to the soil. The use of *M. aegyptia* and *C. procera* biomass as green manure is a viable technology for kale producers in monocropping in a semi-arid environment.

**Keywords:** *Brassica oleracea var. acephala*; economic indicators; productivity; green manuring.

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## Introduction

Kale (*Brassica oleracea*) is one of the most cultivated brassicas worldwide. In the Brassicaceae family, butter-kale (*B. oleracea var. acephala*) is the most cultivated vegetable in Brazil, and its consumption has gradually increased due to new culinary uses and recent scientific discoveries regarding its nutraceutical properties (Oliveira et al., 2019).

Additionally, among the brassica species, it has the highest nutrient concentrations and is notable for its high nutritional value (Freire, Silva, Medeiros, & Silva, 2019). This species is commonly cultivated by family farmers on small properties and provides a quick economic return with relatively low costs compared to other vegetables. However, most of the butter-kale production systems still follow conventional practices (Freire et al., 2019), resulting in high production costs for small-scale producers and environmental contamination over time.

To address these challenges, organic fertilization emerges as an alternative system to enhance soil properties, improve soil fertility, benefit soil biodiversity, and boost plant productivity (Silva et al., 2019). Among various organic fertilization methods, green manuring stands out as a practical and effective technique to provide nutrients and organic matter directly to the cultivation area (Sediyama, Santos, & Lima, 2014).

This technique plays a vital role in improving soil texture and structure, reducing the formation of compacted layers, and adding carbon and nitrogen to the soil, significantly enhancing its physical, chemical, and biological properties while promoting soil conservation (Silva et al., 2020). Green manure has been embraced by producers as a strategy for sustainable agricultural production systems.

In this context, the use of spontaneous species as green manure is gaining prominence, including the hairy woodrose (*Merremia aegyptia*) and roostertree (*Calotropis procera*), which have become valuable options for production systems, as these species are found throughout the Caatinga biome. Hairy woodrose exhibits rapid growth, with an average dry mass production of around 4,000 kg $ha^{-1}$, nitrogen and potassium contents of approximately 19.76 and 34.28 g $kg^{-1}$ of dry matter, and a C:N ratio of 25/1 (Oliveira et al., 2017). Roostertree is available year-round, allowing up to three annual cuts, with an average dry mass production of around 3,000 kg $ha^{-1}$ per cut (120 days), totaling 9 ton $ha^{-1}$ per year (Costa, Medeiros, Alves, & Medeiros, 2009). It contains nitrogen and potassium contents of approximately 18.40 and 24.50 g $kg^{-1}$ in dry matter, with a C:N ratio of 25/1 (Nunes et al., 2018). These native plants have already demonstrated their viability as green manure for leafy vegetables such as lettuce (Souza et al., 2017) and coriander (Ferreira et al., 2022).

Given the above, our goal was to agronomically and economically optimize the green mass productivity of kale and its agronomic components when fertilized with equivalent biomass amounts of the spontaneous species hairy woodrose and roostertree from the Caatinga biome in two cropping seasons.

## Material and methods

### Experiment location

Two experiments were conducted from September to November 2021 and from January to March 2022 at the Experimental Farm 'Rafael Fernandes' of the *Universidade Federal Rural do Semi-Árido* – UFERSA (Federal Rural University of the Semi-Arid), located in the Lagoinha district, roughly 20 km from Mossoró, Rio Grande do Norte State, Brazil. The geographical coordinates of the experimental area are as follows: 5°03'37" S, 37°23'50" W, with an altitude of 80 m.

The climate in this region, classified according to the Köppen Geiger classification as (*BShw*), is dry and extremely hot, characterized by two distinct seasons: a dry season, which typically spans from June to January, and a rainy season, occurring from February to May (Beck et al., 2018). Table 1 presents the average climatic data for the experimental period (Laboratório de Instrumentação Meteorologia e Climatologia [LABIMC], 2022).

**Table 1.** Climatic data during kale development and growth periods in the 2021 and 2022 cropping seasons.

| Cropping seasons | Temperature (°C) | | | Relative humidity (%) | Solar radiation (MJ $m^{-2}$) | Wind speed (m $s^{-1}$) |
|---|---|---|---|---|---|---|
| | Minimum | Mean | Maximum | | | |
| 2021 | 24.26 | 29.49 | 36.61 | 59.97 | 21.11 | 2.78-10.31 |
| 2022 | 24.39 | 28.28 | 34.04 | 73.20 | 17.14 | 1.73-8.09 |

Figure 1 illustrates the average temperatures and relative humidity of the daily air after transplanting the kale during both cropping seasons.

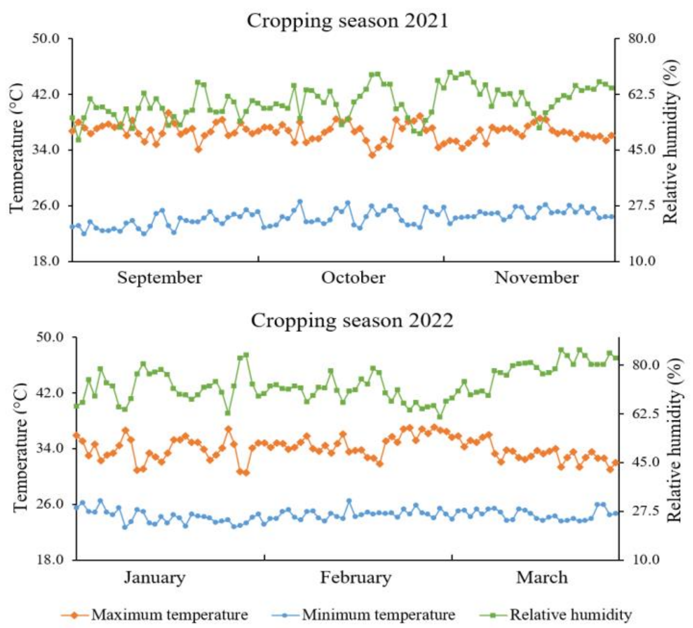


**Figure 1.** Daily averages of temperatures and air relative humidity during the kale cropping periods in 2021 (S1) and 2022 (S2).

The soils in the experimental areas were classified as Dystrophic Red Yellow Latosol (Oxisols - Soil taxonomy USDA) with a sandy loam texture (Santos et al., 2018). Prior to setting up the experiments, simple soil samples were collected from the 0-20 cm depth layer, homogenized to create composite samples, and sent to the Laboratory of Water, Soil, and Plant Tissue Analysis at the Federal Institute of Education, Science, and Technology of Ceará - Campus Limoeiro do Norte, for the determination of their chemical attributes. The results of these analyses are presented in Table 2.

**Table 2.** Chemical analysis of the soil before incorporation of spontaneous species biomass (*Merremia aegyptia* and *Calotropis procera*) in the first (S1) and in the second (S2) cropping areas.

| Cropping seasons | C | OM | pH | EC | K | Ca | Mg | Na | P | Cu | Fe | Mn | Zn | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | --- g kg$^{-1}$--- | | ($H_2O$) | dS m$^{-1}$ | -------- mmol$_c$ dm$^{-3}$ ------ | | | | ------------------ mg dm$^{-3}$ ---------------------- | | | | | |
| 2021 ($S_1$) | 6.90 | 11.90 | 6.30 | 0.44 | 2.36 | 2.25 | 4.80 | 1.73 | 24.00 | 0.50 | 5.70 | 11.20 | 3.70 | 0.58 |
| 2022 ($S_2$) | 7.52 | 12.97 | 6.60 | 0.56 | 2.59 | 2.37 | 6.50 | 2.30 | 32.00 | 0.30 | 4.80 | 6.10 | 2.70 | 0.50 |

*C: carbon; OM: organic matter; pH: hydrogen ionic potential; EC: electrical conductivity; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; P: phosphorus; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; B: boron. (Extractors: P, Na, and K - Mehlich; Ca, Mg, and Al - KCL; H+Al - calcium acetate; pH (in water): 1:2.5 / Cu, Zn, Mn, and Fe – DTPA; B – HCl).

## Experimental design and treatments

A complete randomized block design was employed for both experiments, consisting of five treatments and five replications. Treatments involved equivalent amounts of hairy woodrose (*Merremia aegyptia*) and roostertree (*Calotropis procera*) biomass, at doses of 16, 29, 42, 55, and 68 ton ha$^{-1}$ on a dry basis (material dried at room temperature). In each experiment, plots were planted with kale without fertilizer (control) and with mineral fertilizer for comparison. Mineral fertilizer application followed the recommendations of Trani et al. (2015), with foundation fertilization consisting of 257 kg ha$^{-1}$ of MAP (monoammonium phosphate) and 111 kg ha$^{-1}$ of KCl (potassium chloride). Topdressing was performed at 20, 40, and 60 days after transplanting (DAT) using 7 kg ha$^{-1}$ of MAP, 58 kg ha$^{-1}$ of urea, and 24 kg ha$^{-1}$ of KCl at each application.

The experimental plot consisted of five rows of kale, with five plants per row, planted at a spacing of 0.80 m x 0.40 m (Trani et al., 2015), resulting in an estimated population of 31,250 plants per hectare. The total area of the experimental plot was 8.00 m², with a harvest area of 2.88 m² (Figure 2). The kale cultivar used was Georgia Butter, known for its large, tender, and soft leaves with protruding ribs, making it easy to cultivate and resilient to climatic variations.

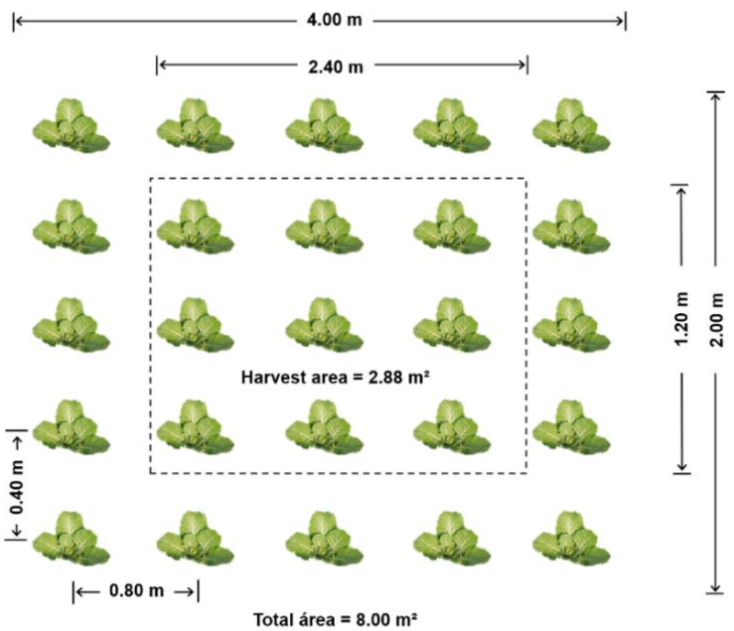


**Figure 2.** Experimental plot diagram for kale plants spaced in 0.80 m x 0.40 m.

## Crop management

Soil preparation involved mechanical cleaning of the experimental areas using a tractor with a plow, followed by harrowing and bed formation using a rotary tiller. Subsequently, pre-planting solarization was conducted for 30 days using 30 μm transparent plastic (Vulca Brilho Bril Fles), following the method recommended by Silva et al. (2017). This method aims to reduce the population of phytopathogens in the soil that may negatively impact the productivity of broadleaf crops.

Green manures for kale fertilization were obtained from hairy woodrose and roostertree plants, collected from native vegetation in various locations in the rural area of Mossoró, Rio Grande do Norte State, Brazil, before they began flowering. After collection, the plants were crushed into fragments measuring two to three centimeters, which were dehydrated at room temperature until their moisture content reached approximately 10%. Subsequently, these fragments underwent laboratory analysis to determine their chemical compositions, as shown in Table 3.

**Table 3.** Macronutrient chemical analysis of dry biomass from *Merremia aegyptia* and *Calotropis procera* green manures in the first and second cropping seasons.

| Green manures | Macronutrient content of green manures (g kg$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | N* | P | K | Ca | Mg | C:N |
| *M. aegyptia* 2021 | 20.56 | 2.83 | 37.08 | 19.35 | 7.07 | 25:1 |
| C. *procera* 2021 | 15.14 | 2.96 | 24.84 | 17.00 | 9.20 | 27:1 |
| *M. aegyptia* 2022 | 18.55 | 1.89 | 38.68 | 9.30 | 7.03 | 25:1 |
| *C. procera* 2022 | 14.09 | 1.54 | 22.72 | 16.30 | 13.50 | 27:1 |

*N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; C:N: carbon/nitrogen ratio.

Green manure used consisted of equal amounts of *M. aegyptia* and *C. procera* biomass at a 1:1 proportion. Green manure dry mass was incorporated manually into the soil using hoes 20 DAT within the 0-20 m depth layer, according to each treatment (Nunes et al., 2018). Plants were irrigated twice daily through micro-sprinkling, in the morning and afternoon, during the experimental period. Water supply was determined based on crop coefficient values (average Kc = 0.93) (Maroulli, Melo, & Braga, 2017), ensuring a daily application of approximately 8 mm to maintain the soil at its field capacity and support microorganism activity, considering the low C:N ratio of green manures to favor organic matter mineralization processes.

In both kale cultivation cycles, seedlings were produced in rigid plastic trays with 200 cells, containing earthworm humus as substrate, within a greenhouse covered with translucent white plastic. Initially, three to five seeds were placed per cell, and after seven days of germination, the first thinning was carried out, leaving three seedlings per cell. After fifteen days, the second thinning was performed, retaining only one seedling per cell. Transplanting to the field occurred at 33 days after sowing (DAS) on 09/08/2021, in the first cycle, and at 28 DAS on 01/04/2022 in the second cycle of cultivation.

Manual weeding was performed as needed throughout the growth cycle. Pest and disease management involved the use of Azamax and Trichodermil products. Kale harvests took place at 40, 55, 70, and 85 days after transplanting (DAT) in both cultivation cycles.

## Evaluated characteristics

In a random sample of five plants from the harvest area, several agronomic traits of kale were evaluated, including plant height (cm), measured from ground level to the tip of the tallest leaves; dry mass of commercial shoot leaves and total dry mass of shoot leaves (g), determined by drying in an oven with forced air circulation at 65°C until constant weight was achieved, and expressed in ton ha$^{-1}$. The number of commercial leaves per plant (consisting of leaves with a length of 25 to 30 cm, free from injuries or deformities) and total number of leaves per plant were obtained by counting all the leaves except unexpanded ones and those on the shoots. The productivity of commercial leaves (composed of leaves with a length of 25 to 30 cm, free from injuries or deformities) and total leaf productivity were calculated based on the fresh mass of commercial and total plant leaves in the harvest area and expressed in ton ha$^{-1}$. The number of leaf packets per m$^2$ was determined by multiplying the plant density (3.13 plants per m$^2$) by the ratio of the number of commercial leaves to the number of leaves in 1 packet (5 leaves).

In addition to these agronomic traits, various economic indicators were quantified, including gross income (expressed in BRL ha$^{-1}$), calculated by multiplying the yield of kale leafy biomass in each treatment by the market price paid to the producer (BRL 5.00 per kilogram). Kale was marketed in units called packets, each containing five leaves. Net income was determined by deducting production costs (inputs and services) from gross income for each treatment, expressed in BRL ha$^{-1}$. Prices of inputs and services in effect in April 2022 in the city of Mossoró, Rio Grande do Norte State, Brazil, were considered. The rate of return per Real (BRL) invested was calculated by comparing gross income and production costs for each treatment, and profit margin was determined as the ratio of net income to gross income, expressed as a percentage.

### Statistical analysis

Univariate analysis of variance was conducted for the complete randomized block design to assess kale characteristics using SAS software (SAS, 2015). Assumptions related to homogeneity of variances and normality were tested using Bartlett's test for homogeneity of variances and Shapiro-Wilk statistic for normality, both performed on treatment residuals (SAS, 2015). Subsequently, a regression curve fitting procedure was employed using Table Curve software (Systat Software, 2022) to estimate the behavior of each characteristic or index in relation to the equivalent amounts of *M. aegyptia* and *C. procera* biomass. The F-test was utilized to compare average values between cropping seasons, between the average values of maximum agronomic or economic efficiency, mineral treatment average value, and control treatment (not fertilized).

## Results and discussion

### Agronomic traits of kale

Table 4 reveals significant interactions between cropping seasons and application of equivalent biomass amounts of *Merremia aegyptia* and *Calotropis procera* for all agronomic traits of kale except plant height. These characteristics include the number of commercial leaves per plant, total number of leaves per plant, and number of packets (marketable bunches) per square meter ($m^2$).

**Table 4.** Means of plant height (PH), number of commercial leaves (NCL) per plant, number of total leaves (NTL) per plant, number of leaf packets (marketable bunches) per square meter of kale over the 2021 and 2022 cropping seasons for the control treatment ($T_{nf}$), for the treatment with maximum physical efficiency (MPE), fertilized treatments ($T_f$) using green manures and mineral fertilization ($T_{mf}$) with chemical fertilizers.

| Comparison treatments | Plant height (cm) | | | NCL per plant | | |
|---|---|---|---|---|---|---|
| | Cropping seasons | | | Cropping seasons | | |
| | 2021 (S1) | 2022 (S2) | 2021- 2022 (mean) | 2021 (S1) | 2022 (S2) | 2021-2022 (mean) |
| Control (without fertilization) ($T_{nf}$) | 24.46 bA | 23.22 bA | 23.84 | 6.0 bA | 3.0 bB | 5.0 |
| MPE Treatment | 29.52 aA | 31.23 aA | 30.17$^+$ | 16.0 aA | 6.0 aB | 11.0$^+$ |
| Fertilized treatments ($T_f$) | 28.38 aA | 29.59 aA | 28.99$^+$ | 16.0 aA | 5.0 aB | 10.0$^+$ |
| Mineral treatment ($T_{mf}$) | 26.86 aA | 25.08 aA | 25.97$^+$ | 7.0 aA | 3.0 bB | 5.0 |
| CV (%) | 6.56 | 5.79 | 6.18 | 15.93 | 31.87 | 20.27 |
| | NTL per plant | | | Number of leaf packets $m^{-2}$ | | |
| Control (without fertilization) ($T_{nf}$) | 33.0 bA | 28.0 bB$^*$ | 31.0 | 4.19 bA | 1.61 bB | 2.90 |
| MPE Treatment | 44.0 aA | 36.0 aB | 40.0$^+$ | 10.40 aA | 3.60 aB | 6.97$^+$ |
| Fertilized treatments ($T_f$) | 43.0 aA | 34.0 aB | 38.0$^+$ | 9.94 aA | 3.22 aB | 6.58$^+$ |
| Mineral treatment ($T_{mf}$) | 35.0 aA | 31.0 aB | 33.0$^+$ | 4.33 bA | 2.03 bB | 3.18 |
| CV (%) | 8.44 | 11.29 | 9.73 | 15.54 | 32.45 | 20.11 |

$^*$Means followed by the same letters, lowercase in the column and uppercase in the rows, do not differ from each other by the F-test at 5% probability. $^+$ Significant difference between fertilized treatments and control ($T_{nf}$).

For each cropping season (S1 and S2), studying the interaction between increasing amounts of *M. aegyptia* and *C. procera* green manures incorporated into the soil revealed a polynomial increase in plant height, number of commercial leaves per plant, total number of leaves per plant, and number of packets per $m^2$ in both seasons (Figure 3). Maximum values were: plant height - 29.52 (S1) and 31.23 cm (S2); number of commercial leaves per plant - 16.0 (S1) and 6.0 (S2); total number of leaves per plant - 44.0 (S1) and 36.0 (S2); and number of packets per $m^2$ - 10.40 (S1) and 3.60 (S2). These maxima occurred, respectively, at specific green manure biomass amounts (in ton $ha^{-1}$): 21.18 (S1) and 43.19 (S2); 58.10 (S1) and 38.10 (S2); 42.75 (S1) and 31.75 (S2); and 57.55 (S1) and 42.92 ton $ha^{-1}$ (S2) (Figure 3). Beyond these peak amounts, all the measured traits decreased towards the highest tested fertilizer levels, reaching maxima of 30.17 cm (plant height), 11 (commercial leaves per plant), 40 (total leaves per plant), and 6.97 (number of packets per $m^2$) for green manure amounts of 40.09, 49.49, 35.22, and 48.63 ton $ha^{-1}$, respectively (Figure 3).

Regarding plant height, averages of maximum physical efficiency (MPE) in treatments receiving green manures ($T_f$) and chemical fertilizers ($T_{mf}$) were significantly different from those of control ($T_{nf}$). However, for the other traits, a significant difference was only registered between treatments receiving green manures ($T_f$) and the control ($T_{nf}$) (Table 4). On the other hand, when comparing cropping seasons, plant height averages showed no differences among the treatments tested. However, for the other traits, all treatments tested differed in the first cropping season (Table 4).

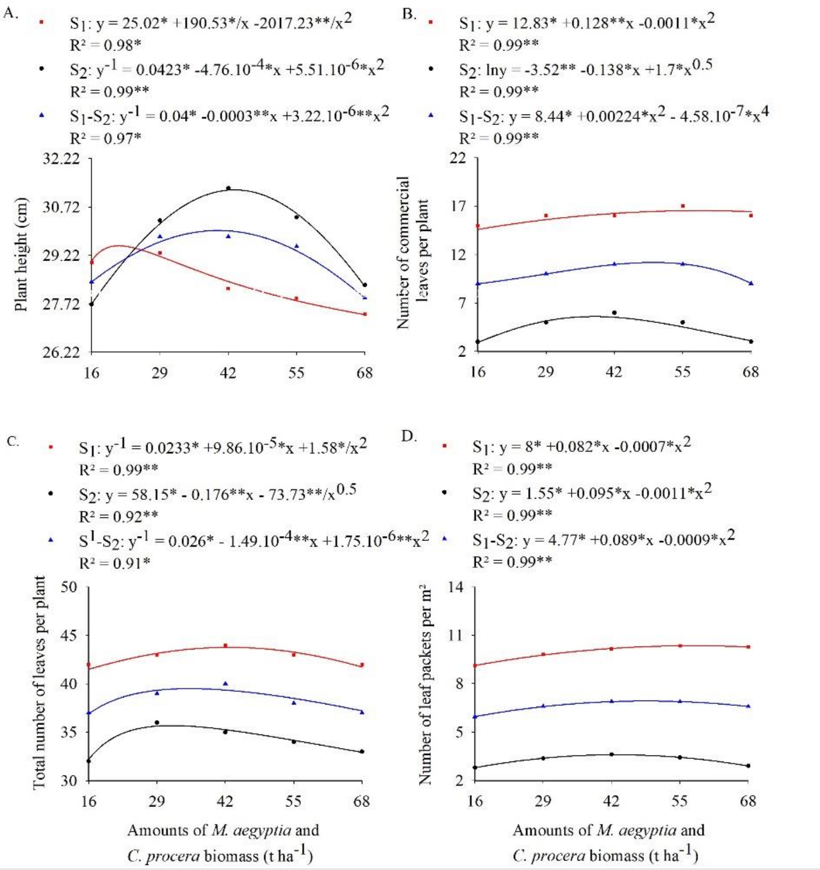


**Figure 3.** Plant height, number of commercial leaves per plant, total number of leaves per plant, and number of leaf packets per square meter as a function of equivalent *Merremia aegyptia* and *Calotropis procera* biomass amounts incorporated into the soil in the 2021 and 2022 cropping seasons.

The polynomial trends observed in all agronomic traits of kale may be explained by the law of maximum, which suggests that the equivalent amounts of *M. aegyptia* and *C. procera* likely caused an excessive supply of certain nutrients in the soil. This excess can potentially lead to either a toxic effect on the plants or a reduced efficiency of other essential elements, resulting in a decline in the values of these traits once the maximum point is reached (Bezerra Neto et al., 2019). Therefore, higher rates of fertilizer application do not necessarily translate into increased yields. Instead, excessive fertilization can hinder the effectiveness of other nutrients and impede the plants' ability to grow and mature to their full potential.

Ferreira et al. (2022) studied different *M. aegyptia* and *C. procera* biomass application amounts in coriander cultivation and found a beneficial effect on its agronomic traits. These authors also observed a polynomial trend for plant height, number of stems per plant, leaf/stem ratio, and number of packets per square meter. Likewise, in cowpea cultivation, Desravines et al. (2022) also reported a beneficial effect of the same green manures and noted a polynomial trend for plant height, green pod length, number of green grains per pod, and green pod yield. Based on these studies, the amount of nutrients provided by hairy woodrose and roostertree green manures proved sufficient to optimize the agronomic traits of kale.

In our study, the difference in agronomic traits between seasons can likely be attributed to better soil and climate conditions in the first season compared to the second.

## Productive traits of kale

Table 5 presents the results of the analysis of variance for the productive traits of kale, including commercial leaf productivity, total leaf productivity, and commercial and total shoot leaf dry masses. Significant interactions between *M. aegyptia* and *C. procera* biomass amounts and cropping seasons were observed for all these productive traits.

**Table 5.** Averages of commercial (CLP) and total (TLP) leaf productivities, and commercial (CLDM) and total (TLDM) leaf dry masses of kale over the 2021 and 2022 cropping seasons for control ($T_{nf}$), maximum physical efficiency (MPE), green manure fertilization ($T_f$), and mineral fertilization ($T_{mf}$).

| Comparison treatments | Productivity of commercial leaves (ton ha$^{-1}$) | | | Productivity of total leaves (ton ha$^{-1}$) | | |
|---|---|---|---|---|---|---|
| | Cropping seasons | | | Cropping seasons | | |
| | 2021 (S1) | 2022 (S2) | 2021-2022 (mean) | 2021 (S1) | 2022 (S2) | 2021-2022 (mean) |
| Control (without fertilization) ($T_{nf}$) | 7.98 bA | 4.47 bB | 6.23 | 17.80 bA* | 3.94 bB | 10.87 |
| MPE Treatment | 25.19 aA | 8.84 aB | 16.92+ | 37.47 aA | 10.76 aB | 23.64+ |
| Fertilized treatments ($T_f$) | 19.64 aA | 7.21 aB | 13.42+ | 35.31 aA | 10.08 aB | 22.69+ |
| Mineral treatment ($T_{mf}$) | 8.21 bA | 6.36 bB | 7.29 | 19.38 aA | 7.22 aB | 13.28+ |
| CV (%) | 11.80 | 6.45 | 12.13 | 9.41 | 20.37 | 12.17 |
| | Dry mass of commercial leaves (ton ha$^{-1}$) | | | Total dry mass of leaves (ton ha$^{-1}$) | | |
| Control (without fertilization) ($T_{nf}$) | 0.70 bA | 0.29 bB | 0.49 | 1.68 bA | 1.14 bB | 1.41 |
| MPE Treatment | 2.48 aA | 0.72 aB | 1.57+ | 4.05 aA | 1.86 aB | 2.96+ |
| Fertilized treatments ($T_f$) | 2.29 aA | 0.60 aB | 1.45+ | 3.91 aA | 1.66 aB | 2.79+ |
| Mineral treatment ($T_{mf}$) | 0.92 bA | 0.32 bB | 0.62 | 2.54 aA | 1.31 aB | 1.92+ |
| CV (%) | 18.55 | 31.63 | 22.72 | 9.64 | 13.98 | 11.23 |

*Means followed by the same letters, lowercase in the column and uppercase in the rows, do not differ from each other by the F-test at 5% probability.
+Significant difference between fertilized treatments and control ($T_{nf}$).

The interaction between green manure amounts and kale's commercial and total leaf productivities (CLP and TLP), commercial and total leaf dry masses (CLDM and TLDM) showed a polynomial behavior in both seasons (S1 and S2) separately. This trend demonstrated increased productivity as equivalent *M. aegyptia* and *C. procera* biomass amounts were incorporated into the soil. Maximum values were reached at 25.19 (S1) and 8.84 (S2) for CLP, 37.47 (S1) and 10.76 (S2) for TLP, 2.48 (S1) and 0.72 (S2) for CLDM, and 4.05 (S1) and 1.86 (S2) for TLDM. These peaks respectively corresponded to *M. aegyptia* and *C. procera* biomass amounts of 55.33 (S1) and 61.54 (S2) ton ha$^{-1}$ for CLP, 68.00 (S1) and 45.24 (S2) ton ha$^{-1}$ for TLP, 64.56 (S1) and 52.60 (S2) ton ha$^{-1}$ for CLDM, and 46.34 (S1) and 44.38 (S2) ton ha$^{-1}$ for TLDM. Beyond these points, further increases in fertilizer amounts led to a decrease in productivity (Figure 4).

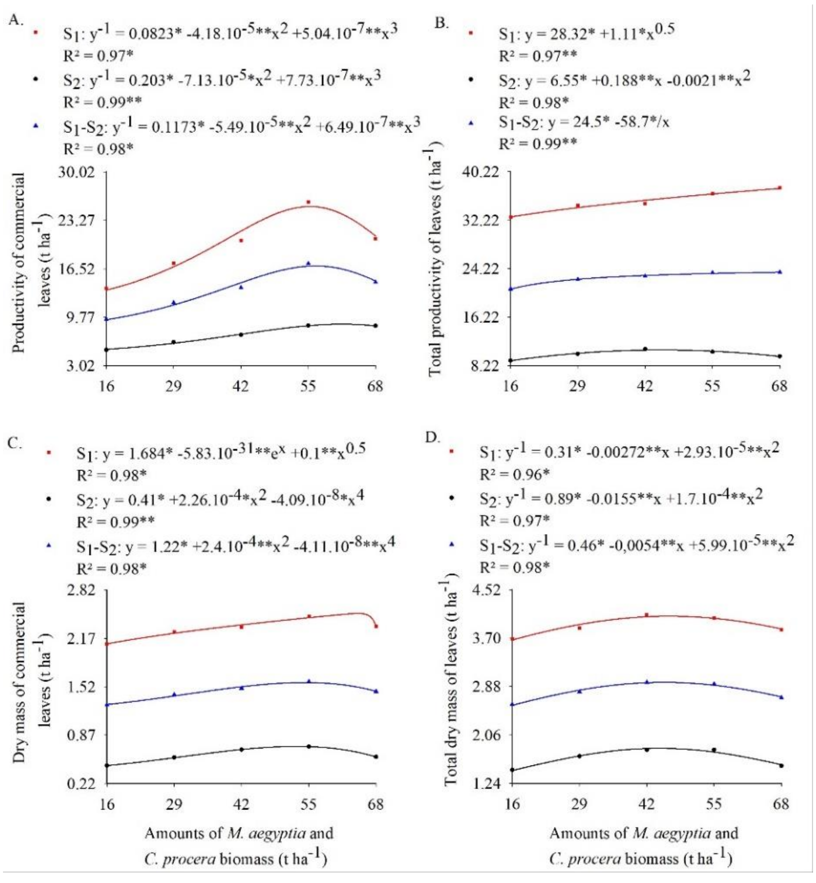


**Figure 4.** Commercial leaf productivity, total leaf productivity, commercial leaf dry mass, and total leaf dry mass of kale plants as a function of equivalent *Merremia aegyptia* and *Calotropis procera* biomass amounts incorporated into the soil in the 2021 and 2022 cropping seasons.

Analyzing the MPE across seasons revealed a polynomial response to increasing green manure amounts. Peak values for CLP and TLP (16.92 and 23.64, respectively) and CLDM and TLDM (1.57 and 2.96, respectively) were reached at green manure additions of 56.41, 68.00, 54.16, and 45.28 ton $ha^{-1}$, before declining towards the highest fertilizer levels (Figure 4).

Compared to the control ($T_{nf}$), treatments receiving green manure ($T_f$) and mineral ($T_{mf}$) fertilizers showed significant differences in TLP and TLDM. However, only MPE and $T_f$ differed significantly from $T_{nf}$ for CLP and CLDM (Table 5). Additionally, the first cropping season differed from the second for all examined productive traits (Table 5).

The observed polynomial optimization of kale's productive traits can also be explained by the law of the maximum, lowering yields (Almeida et al., 2015). Additionally, these traits may be linked to the specific behavior of leafy crops and synchrony between green manure decomposition and mineralization and the crop's peak nutrient demand (Fontanétti et al., 2006). Factors like N content, C:N ratio, lignin and polyphenol levels, and their interaction with climate, microorganisms, and soil conditions influence the speed of those processes (Diniz et al., 2014). The C:N ratios of the tested green manures (20:1 for *M. aegyptia* and 25:1 for *C. procera*) facilitated rapid decomposition and nutrient release.

The macronutrient content of the tested green manures met the needs of the kale plants. Taiz, Zeiger, Moller, and Murphy (2017) highlight how nitrogen promotes plant growth and leaf number and weight. Potassium significantly influences photosynthesis, while phosphorus affects leaf formation and weight, impacting both productivity and quality of the harvested product.

The lower productive potential of kale in the second season appears to be primarily due to less favorable soil and climate conditions. Taiz et al. (2017) state that biomass accumulation directly correlates with leaf area. Larger leaf surfaces tend to produce more photosynthates. In this experiment, the effectiveness of green manure translated into leaf productivity because of the nutrient content provided by the used species. According to Batista, Inoue, Esper Neto, and Muniz (2018), improved plant foliage reflects the availability of soil nutrients, particularly macronutrients. Therefore, the lower productivity in the second season likely resulted from the high incidence of rainfall that slowed plant growth, reduced leaf quality, and promoted pest infestation (aphids and lepidopteran larvae).

## Kale economic indicators

Analysis of variance for kale economic indicators (gross income, net income, rate of return, and profit margin) revealed significant interactions between green manure amounts (*M. aegyptia* and *C. procera* biomass) and cropping seasons in all these metrics (Table 6).

**Table 6.** Averages of gross income (GI), net income (NI), rate of return (RR), and profit margin (PM) for kale over the 2021 and 2022 cropping seasons for control ($T_{nf}$), maximum physical efficiency (MPE), green manure ($T_f$), and mineral ($T_{mf}$) fertilizations.

| Comparison treatments | Gross income (R$ $ha^{-1}$) | | | Net income (R$ $ha^{-1}$) | | |
|---|---|---|---|---|---|---|
| | Cropping seasons | | | Cropping seasons | | |
| | 2021 (S1) | 2022 (S2) | 2021-2022 (mean) | 2021 (S1) | 2022 (S2) | 2021-2022 (mean) |
| Control (without fertilization) ($T_{nf}$) | 39872.36 bA | 22371.53 bB | 31121.95 | 20433.52 bA* | 2932.68 bB | 11683.10 |
| MEE Treatment | 125565.54 aA | 44085.69 aB | 84514.86+ | 89204.03 aA | 9155.59 aB | 47841.44+ |
| Fertilized treatments ($T_f$) | 98198.61 aA | 36045.35 aB | 67121.98+ | 65155.50 aA | 3002.24 bB | 34078.87+ |
| Mineral treatment ($T_{mf}$) | 41057.22 aA | 31809.03 aB | 36433.13+ | 15800.02 bA | 6551.82 aB | 11175.92 |
| CV (%) | 11.36 | 4.50 | 11.54 | 17.94 | 43.07 | 24.07 |
| | Rate of return | | | Profit margin (%) | | |
| Control (without fertilization) ($T_{nf}$) | 2.05 bA | 1.15 bB | 1.60 | 48.92 bA | 12.89 bB | 30.90 |
| MEE Treatment | 3.75 aA | 1.21 aB | 2.47+ | 73.68 aA | 18.01 aB | 45.86+ |
| Fertilized treatments ($T_f$) | 2.97 aA | 1.09 bB | 2.03+ | 65.62 aA | 7.87 cB | 36.75+ |
| Mineral treatment ($T_{mf}$) | 1.63 bA | 1.26 aB | 1.44 | 37.22 cA | 20.35 aB | 28.78 |
| CV (%) | 10.77 | 4.65 | 10.87 | 10.22 | 37.83 | 14.66 |

*Means followed by the same letters, lowercase in the column and uppercase in the rows, do not differ from each other by the F-test at 5% probability. + Significant difference between fertilized treatments and control ($T_{nf}$).

Analyzing the interactions within each cropping season (Figure 5), we observed increasing trends in gross income, net income, rate of return, and profit margin for both seasons (S1 and S2) as equivalent *M. aegyptia* and *C. procera* biomass amounts increased, following a polynomial model. Peak values (shown in BRL $ha^{-1}$) were reached at specific biomass additions: S1) Gross income: 125,565.54 (55.33 ton $ha^{-1}$), Net income:

89,204.03 (53.44 ton $ha^{-1}$), Rate of return: 3.75 reals per real invested (64.28 ton $ha^{-1}$) Profit margin: 73.68% (64.12 ton $ha^{-1}$); S2) Gross income: 44,085.69 (61.55 ton $ha^{-1}$), Net income: 9,155.59 (64.83 ton $ha^{-1}$), Rate of return: 1.21 reals per real invested (64.46 ton $ha^{-1}$), Profit margin: 18.01% (64.44 ton $ha^{-1}$), Beyond these peaks, all economic indicators declined towards the highest fertilizer levels (Figure 5).

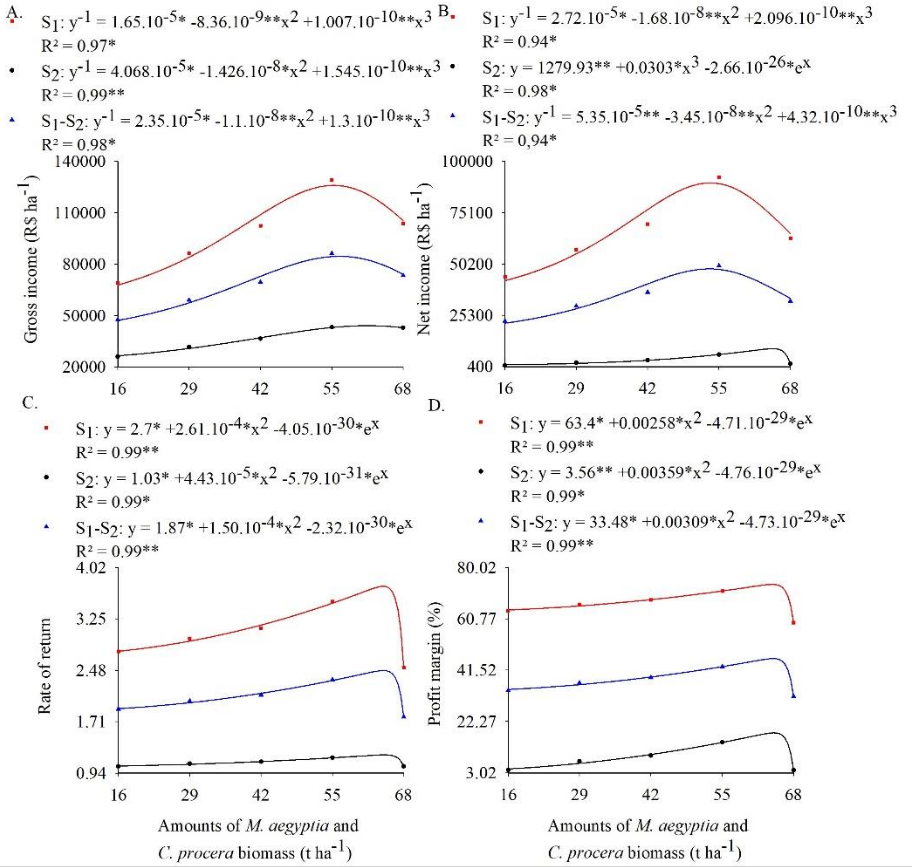


**Figure 5.** Gross income, net income, rate of return, and profit margin for kale crop as a function of equivalent *Merremia aegyptia* and *Calotropis procera* biomass amounts incorporated into the soil in the 2021 and 2022 cropping seasons.

Analyzing the maximum economic efficiencies (MEE) across seasons revealed, similar to productivity, a polynomial response to increasing green manure amounts (Figure 5). Peak values for gross and net income (84,514.86 and 47,841.44 BRL $ha^{-1}$ in S1 and S2, respectively) and for rate of return and profit margin (2.47 reals per real invested and 45.86 %, respectively) were reached at specific biomass additions: 56.42, 53.26, 64.31, and 64.30 ton $ha^{-1}$), declining towards the highest fertilizer levels (Figure 5).

Compared to the control ($T_{nf}$), treatments receiving green manure ($T_f$) and mineral ($T_{mf}$) fertilizers demonstrated significantly higher values in all economic indicators (Table 6). Additionally, a clear distinction was observed between cropping seasons, with the first season consistently outperforming the second across all tested treatments.

The optimized economic performance observed in kale can be attributed to the efficient nutrient availability provided by the green manures, particularly nitrogen, which is crucial for leafy crop growth and yield (Ferreira et al., 2022). Beyond direct nutrient supply, green manure also enhances soil properties, improving physical, chemical, and biological conditions. This fosters favorable development for the crop, ultimately translating productive gains into economic benefits.

As Silva et al. (2020) explain, green manure additions positively impact the soil's physical-chemical structure by increasing organic matter and adjusting density and porosity. These alterations improve water, air, and solute movement within the soil, while slower-decomposing residues provide a gradual release of nutrients for sustained plant uptake. Furthermore, Pereira et al. (2018) highlight the role of incorporated plant material in stimulating microbial activity, leading to efficient nutrient decomposition and transformation, ensuring balanced nutrition for kale throughout its growth cycle.

Notably, the observed maximum physical efficiencies (MEF) from previous analyses translated into peak economic efficiencies across seasons (Table 6). Our findings align with those of Ferreira et al. (2022), who similarly observed optimized agroeconomic performance in coriander cultivation using *M. aegyptia* and *C. procera* green manures and polynomial models.

These combined results demonstrate the potential of green manuring with Caatinga biome species to deliver a sound financial return on investment. This technique empowers leafy vegetable producers to strategically optimize green manure application based on desired cost-benefit outcomes. For family farms, adopting this practice allows entry into new market niches through differentiated product offerings and reduced reliance on external inputs (Melo, Luengo, Costa Júnior, & Butruille, 2017), ultimately presenting a sustainable and resilient alternative.

## Conclusion

Peak physical efficiencies for commercial kale leaf productivity (16.92 ton ha$^{-1}$) and leaf packets per square meter (6.97) were achieved with additions of 56.41 and 48.63 ton ha$^{-1}$ of *Merremia aegyptia* and *Calotropis procera* green manures into the soil. Moreover, the highest net income (47,841.44 BRL ha$^{-1}$) and optimized rate of return (2.47 reals for each real invested) occurred with 53.26 and 64.31 ton ha$^{-1}$ of the green manures, respectively.

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