Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252025v3812604rc

Scientific Article

Optimizing roostertree biomass for arugula production in semi-arid regions

Otimização da biomassa de flor-de-seda na produção de rúcula em regiões semiáridas

Jailma S. S. de Lima[1]*, Francisco Bezerra Neto[1], Iron D. de J. S. do Carmo[2], Jéssica P. P. da Silva[2], Elizangela C. dos Santos[1], Marianne C. de Azevedo[2], Gardênia S. de O. Rodrigues[3], Rebeca M. S. Frutuoso[4]

[1]Department of Agronomic and Forestry Sciences, Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil. [2]Postgraduate Program in Plant Sciences, Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil. [3]Secretaria de Estado de Educação, Cultura, Esporte e Lazer, Mossoró, RN, Brazil. [4]Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil.

ABSTRACT - Enhancing soil fertility in vegetable cultivation presents challenges, notably using green manure from spontaneous species in the Caatinga biome, such as roostertree (*Calotropis procera* [Ait.] R. Br.). This study aimed to evaluate and optimize the physical and economic efficiencies of monocropped arugula, as influenced by varying amounts of roostertree biomass. We employed a randomized block design with seven treatments and five replications. Treatments involved different quantities of *C. procera* biomass (20, 40, 60, 80, and 100 t ha^{-1} on a dry basis), along with two additional treatments in each block: a control (no fertilization) and one with mineral fertilization. The "Cultivada" arugula cultivar was fertilized for maximum productive efficiency using 63.31 t ha^{-1} of *C. procera* dry biomass, yielding 8.45 t ha^{-1}. The highest optimized agroeconomic efficiency, reflecting a net income of BRL 111,007.64 per hectare, was achieved with 59.26 t ha^{-1} of *C. procera* dry biomass. The return rate was BRL 4.65 for every real investment, with a profitability index of 77.38%. Thus, using *C. procera* biomass as green manure is a viable technology for arugula producers in semi-arid regions.

Keywords: Green manuring. *Calotropis procera*. *Eruca sativa*. Monocropping. Agro-economic optimization.

RESUMO - O aumento da fertilidade do solo no cultivo de hortaliças apresenta desafios, notadamente usando adubo verde de espécies espontâneas do bioma Caatinga, como a flor-de-seda (*Calotropis procera* [Ait.] R. Br.). Este estudo teve como objetivo avaliar e otimizar as eficiências física e econômica da rúcula em monocultivo, influenciadas por quantidades variáveis de biomassa de flor-de-seda. Um delineamento em blocos casualizados com sete tratamentos e cinco repetições foi utilizado. Os tratamentos consistiram de diferentes quantidades de biomassa de *C. procera* (20, 40, 60, 80 e 100 t ha^{-1} em base seca), juntamente com dois tratamentos adicionais em cada bloco: um controle (sem fertilização) e um com fertilização mineral. A cultivar de rúcula "Cultivada" foi adubada para máxima eficiência produtiva usando 63,31 t ha^{-1} de biomassa seca de *C. procera*, rendendo 8,45 t ha^{-1}. A maior eficiência agroeconômica otimizada, refletindo uma renda líquida de R$ 111.007,64 por hectare, foi alcançada com 59,26 t ha^{-1} de biomassa seca de *C. procera*. A taxa de retorno foi de R$ 4,65 para cada real investido, com um índice de rentabilidade de 77,38%. Assim, utilizar biomassa de *C. procera* como adubo verde é uma tecnologia viável para produtores de rúcula em regiões semiáridas.

Palavras-chave: Adubação verde. *Calotropis procera*. *Eruca sativa*. Monocultivo. Otimização agroeconômica.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: April 4, 2024.
Accepted in: July 10, 2024.

***Corresponding author:**
<jailma@ufersa.edu.br>

INTRODUCTION

Arugula (*Eruca sativa* Mill.) is a leafy vegetable renowned for its high nutritional value, containing vitamins A and C, and minerals such as calcium, iron, potassium, and manganese. It also offers anti-inflammatory and detoxifying benefits for the human body (PLIZ et al., 2023). Its consumption in Brazil is on the rise, and it is favored for its distinctive flavor in salads (BELL; WAGSTAFF, 2019). Furthermore, its organic production is expanding in the region, driven by consumer demand for a healthier diet and the goal of promoting environmental conservation through practices that exclude chemical fertilizers and pesticides (FAO, 2023).

Sustainable production systems that enhance food and environmental security can be achieved using organic fertilizers. These fertilizers optimize the organic matter in the soil, enrich the microbiota, improve fertility, and increase crop yields (FAO, 2023; SAYARA et al., 2020). According to Carneiro et al. (2022), sustainable practices include utilizing local resources, recycling nutrients with legumes or spontaneous plants, and incorporating crop residues and organic compounds for green manure production.

Green manuring is a prevalent management practice in the organic cultivation of food crops, fruit trees, and vegetables in semi-arid regions. The selection of suitable plants for green manuring depends on their phytomass production potential, nutrient absorption, and accumulation capabilities, favorable C/N ratio for rapid decomposition and nutrient release, and low cost. Spontaneous species from the Caatinga biome, such as *Calotropis procera*, significantly contribute to the nutrient supply required by vegetables, offering an agroecological and sustainable production method (SOUZA et al., 2017).

Research indicates that *C. procera* green manure positively impacts the production of tuberous vegetables such as radishes. Silva et al. (2023) noted that adding 50.86 t ha^{-1} of *C. procera* biomass to the soil maximized radish yield at 9.56 t ha^{-1} and achieved a maximum net income of BRL 37,641.08 ha^{-1} with 44.39 t ha^{-1} of green manure. Additionally, Vieira et al. (2018) and Silva et al. (2018) documented maximum yields of 3.05 t ha^{-1} for green cowpea grains and 18.16 t ha^{-1} for green lettuce leaves with 61.00 and 40.29 t ha^{-1} of *C. procera* added to the soil, respectively. Additions of 53.57 and 32.20 t ha^{-1} of green manure to the soil can result in peak economic efficiencies with net incomes of BRL 8,701.42 and BRL 7,546.31 ha^{-1}.

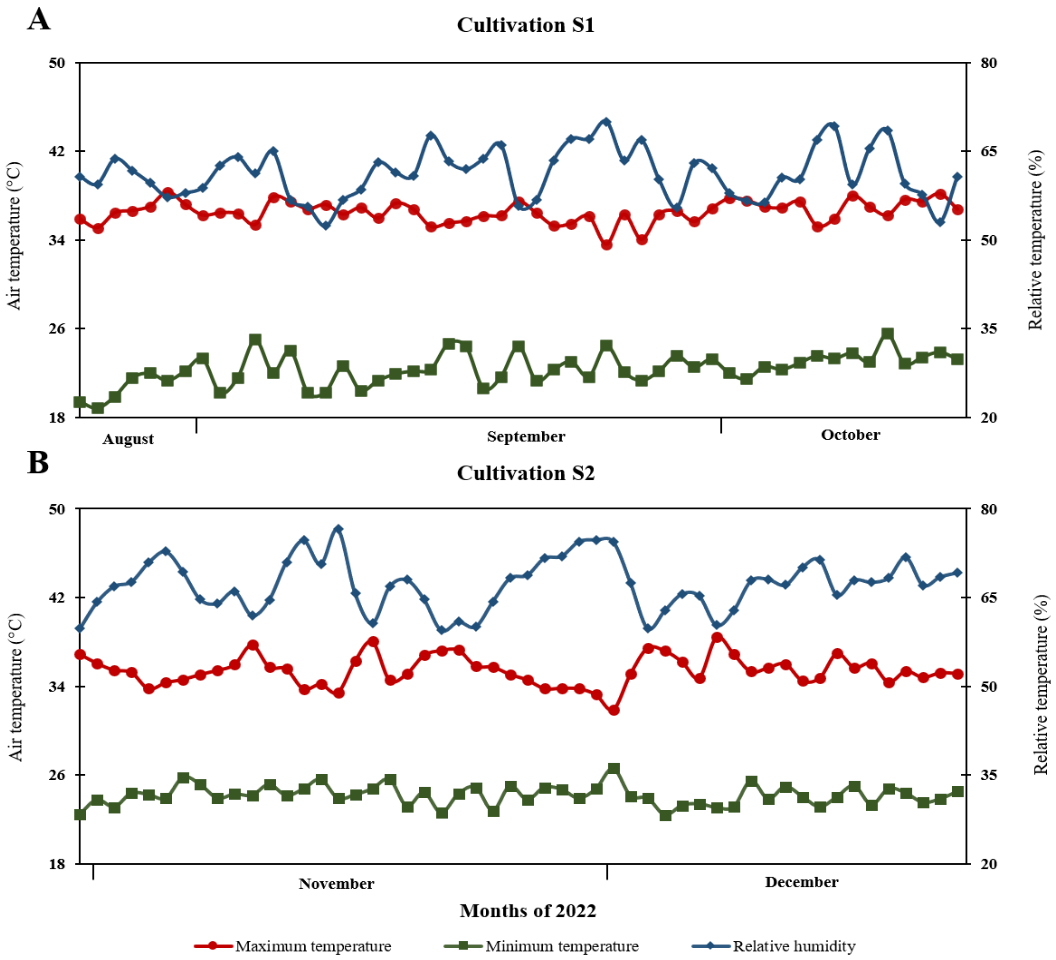
Consequently, this study aims to agro-economically optimize the yield of green arugula leaves and their components when fertilized with varying amounts of *C. procera* dry biomass, leveraging this spontaneous species from the Caatinga Biome across two cultivation seasons.

MATERIALS AND METHODS

Two experiments were conducted at the Experimental Farm 'Rafael Fernandes,' affiliated with the Universidade Federal Rural do Semi-Árido (UFERSA), located in the district of Lagoinha, 20 km from Mossoró, RN, Brazil. The geographical coordinates are 5° 03' 37" south latitude and 37° 23' 50" west longitude, at an approximate altitude of 80 m. The first season (S_1) ran from August to October 2022, and the second (S_2) from October to December 2022.

The region's climate is classified as dry and extremely hot according to the Köppen system, characterized by a dry season from June to January and a rainy season from February to May (BECK et al., 2018).

Climatic data for S_1 included average minimum and maximum temperatures of 22.34 °C and 36.49 °C, global solar radiation of 20.75 MJ m^{-2}, relative air humidity of 61.23%, and accumulated rainfall of 6.35 mm. S_2 recorded average minimum and maximum temperatures of 24.17 °C and 35.42 °C, global solar radiation of 20.18 MJ m^{-2}, relative air humidity of 67.22%, and accumulated rainfall of 5.08 mm. Extreme temperature records were 18.8 °C and 38.32 °C during S_1, and 22.38 °C and 38.41 °C in S_2 (Figure 1).



Source: LABIMC, 2023.

Figure 1. Daily averages of temperature and relative humidity during arugula growth and development periods for S_1 and S_2 cultivations.

The soil in the experimental areas was classified as typical Dystrophic Red Yellow Argisol with a sandy loam texture (SANTOS et al., 2018). Surface soil samples (0-20 cm) were collected and homogenized to form a composite sample. Laboratory analysis according to Teixeira et al. (2017) revealed chemical attributes: hydrogenionic potential (pH) in H_2O = 7.4; electrical conductivity (EC) = 0.34 dS m^{-1}; organic matter (OM) = 7.84 g kg^{-1}; organic carbon (OC) = 4.55 g kg^{-1}; phosphorus (P) = 6.0 mg dm^{-3}; potassium (K) = 1.32 mg dm^{-3}; calcium (Ca) = 15.9 mmol$_c$ dm^{-3}; magnesium (Mg) = 5.9 mmol$_c$ dm^{-3}; sodium (Na) = 1.74 mg dm^{-3}; copper (Cu) = 0.20 mg dm^{-3}; iron (Fe) = 5.2 mg dm^{-3}; manganese (Mn) = 10.8 mg dm^{-3}; zinc (Zn) = 1.1 mg dm^{-3}; and boron (B) = 0.34 mg dm^{-3}; base sum (SB) = 24.9 mg dm^{-3}; coarse sand = 475 g kg^{-1}; fine sand = 433 g kg^{-1}; silt = 46 g kg^{-1}; clay = 46 g kg^{-1}; soil density = 1.52 g cm^{-3}; and particle density = 2.84 g cm^{-3}.

The research employed a randomized complete block design with seven treatments and five replications, testing varying doses of *Calotropis procera* (roostertree) biomass (20, 40, 60, 80, and 100 t ha^{-1}, dry basis). Additionally, each experiment included a control without fertilizer and another with mineral fertilizer for comparison. Based on soil analysis and Trani et al. (2018) recommendations for arugula, mineral fertilization occurred in two phases: basal application seven days pre-planting (30 kg ha^{-1} N, 320 kg ha^{-1} P_2O_5, 50 kg ha^{-1} K_2O, 2 kg ha^{-1} B) and top dressing at 7, 14, and 21 days post-germination (140 kg ha^{-1} N, 30 kg ha^{-1} P_2O_5, 50 kg ha^{-1} K_2O).

Each plot consisted of six rows of the arugula cultivar 'Cultivada,' with 24 plants per row, spaced 0.05 m × 0.20 m. The plot area was 1.44 m² with a harvest area of 0.80 m². The cultivar "Cultivada" has dark green, lobed, and jagged leaves, with characteristic aroma and flavor (slightly spicy and bitter).

The experimental areas were first mechanically cleared using a tractor for plowing and harrowing. The beds were then formed using a rotary hoe, followed by solarization using transparent plastic (Vulca Brilho Bril Flex® at 30 microns) for 30 days before planting. This process aimed to reduce or eliminate soil phytopathogens and weeds that could adversely affect crop development (SILVA et al., 2017).

Calotropis procera, used as green manure, was harvested from native vegetation near urban and rural areas of Mossoró-RN before its flowering stage when it accumulates the freshest biomass. The plants were transported to the Didactic Garden at UFERSA's Agricultural Sciences Center (CCA), where they were shredded into 2-3 cm pieces using a conventional forage machine. The shredded material was then sun-dried for five days until it reached a moisture content of about 10%. Samples were collected for laboratory analysis to determine their chemical composition (Table 1).

Table 1. Chemical composition of *Calotropis procera* biomass in arugula experiments during S_1 and S_2 seasons.

Cultivation	C*	N	C: N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B
	.... g kg^{-1}...		ratio	.... g kg^{-1}					.... mg kg^{-1}				
S_1	410.42	13.59	30	18.29	26.67	14.21	12.40	3.79	86.62	5.34	27.23	70.06	4.53
S_2	399.13	15.41	26	14.72	24.27	13.75	11.19	4.70	104.06	6.76	26.99	79.44	5.33

* C: Carbon, N: nitrogen, P: Phosphorus, K: Potassium, Ca: Calcium, Mg: Magnesium, S: Sulfur, B: Boron, Fe: Iron, Cu: Copper, Mn: Manganese and Zn: Zinc.

After solarization, green manure was incorporated 20 days before sowing, uniformly mixed into the top 0-20 cm of soil as per treatment specifications. Planting occurred via direct sowing in 2 cm deep holes, with three to four seeds per hole. The first season was planted on 09/14/2022, and the second on 11/21/2022. Thinning was done at eight days for the first season and thirteen days for the second, leaving one plant per hole.

Cultural management included manual weeding every seven days and daily irrigation via micro-sprinkler in two shifts (morning and afternoon), delivering a water depth of approximately 8 mm per day to maintain soil field capacity, support soil microorganism activity, and promote organic matter mineralization (ALVES et al., 2017). Arugula was harvested 30 days after planting in both seasons.

Agronomic assessments involved measuring plant height from the petiole base to the highest leaf tip, counting leaves larger than 4 cm per plant, and determining leaf area (cm²) using a LI-COR 3100® leaf area meter on ten randomly selected plants. Shoot dry mass was gauged by drying fresh mass at 65°C until a constant mass was achieved, and green mass yield was calculated from the fresh mass harvested, both expressed in tons per hectare.

Economic indicators included gross income (BRL ha^{-1}), calculated by multiplying green mass yield by the market price (BRL 10.00 per kilogram); net income, derived by subtracting production costs from gross income; rate of return per real invested, and profitability index, calculated as the ratio of net income to gross income in percentage terms. Prices of inputs and services were based on October 2022 rates in Mossoró-RN.

Statistical analysis involved univariate analysis of variance for each season to confirm assumptions of normality, homoscedasticity, and additivity were met. A joint analysis checked for homogeneity in the variance of residuals across seasons, with a variance ratio under seven considered homogeneous (PIMENTEL-GOMES, 2022).

Regression analysis using Table Curve 2D software (SYSTAT SOFTWARE, 2022) estimated the maximum physical and economic efficiencies (MPE and MEE) of each characteristic or indicator relative to *C. procera* biomass quantities. Polynomial models selected based on the biological logic of the variable, significance of regression residuals, high coefficients of determination (R^2) value, and significance of regression equation parameters helped express the behavior of each trait. The F-test compared mean values across seasons, including maximum agronomic or economic efficiencies and control treatment averages.

RESULTS AND DISCUSSION

Arugula agronomic traits

Table 2 presents the averages of agronomic characteristics for arugula, including plant height, number of leaves per plant, green mass yield, and dry mass. These traits exhibited significant interactions ($p < 0.05$) between the treatment factors fertilized treatments and cultivations except for the number of leaves per plant, which showed no significant interaction.

Table 2. Averages from control treatment (T_c), maximum physical efficiency (MPE), green manured treatments (T_{gm}), and mineral fertilizer treatment (T_{mf}) for plant height, number of leaves per plant, green mass yield, shoot dry mass, and leaf area index of arugula plants in the cultivations S_1 and S_2.

Treatment	Cultivation			Cultivation		
	(S1)	(S2)	(S1/S2)	(S1)	(S2)	(S1/S2)
	Plant height (cm)			Number of leaves per plant		
T_c	13.24cA	10.79cB	10.63c			5.94c
MPE	15.27bB	18.49bA	16.94b			8.59b
T_{gm}	14.42bA	14.47bA	14.44b			7.49b
T_{mf}	26.31aA	27.04aA	26.68a			11.74a
	Green mass yield (t ha^{-1})			Shoot dry mass (t ha^{-1})		
T_c	4.51cA	3.52cA	5.73c	1.04cA	0.57cB	0.80c
MPE	5.87bB	10.47bA	8.45b	1.25bB	1.63bA	1.47b
T_{gm}	5.25bB	7.57bA	8.73b	1.14bA	1.22 bB	1.08b
T_{mf}	14.78aB	16.39aA	15.58a	3.10aB	3.87aA	3.48a
	Leaf area index (cm^2)					
T_c	631.20cA	619.36cA	625.27c			
MPE	1749.02bB	2238.89bA	1993.95b			
T_{gm}	1244.99bB	1715.17bA	1553.08b			
T_{mf}	3649.30aA	3744.23aA	3696.77a			

*Averages followed by the same lowercase letter within columns and uppercase within rows do not differ statistically from each other by F-test at a 5% probability level.

Regarding maximum physical efficiency (MPE), the control treatment (T_c) differed significantly from green manure (T_{gm}) and mineral fertilizer (T_{mf}) treatments across all evaluated agronomic traits of arugula: plant height, number of leaves, green mass yield, shoot dry mass, and leaf area index. The measurements in these treatments were, respectively, 1.6, 1.4, 1.5, 1.8, and 3.2 times higher than those in the control treatment. Across the two seasons, treatments fertilized with *Calotropis procera* biomass showed variations, with season 2 (S2) outperforming season 1 (S1) in all characteristics except the number of leaves per plant, which showed no significant seasonal interaction.

Mineral treatment displayed significant differences only in green and dry mass yields, with higher yields in S2. For the control treatment, significant seasonal differences were noted only in plant height and shoot dry mass, with S1 exhibiting higher values (Table 2). These findings align with studies by Silva et al. (2023) and Silva et al. (2024), who reported comparable results for radish and beet crops, respectively. The higher relative humidity during S2 likely enhanced crop performance, as supported by Silva et al. (2017), who reported the effect of meteorological factors on radish root yield fertilized with *C. procera*.

The higher green mass yields observed with mineral treatment compared to green manure treatments may relate to nitrogen (N), phosphorus (P), and potassium (K) concentrations provided by inorganic fertilizers, particularly N. Urea, as a soluble N source, is readily absorbed by plants, enhancing growth efficiency (PEREIRA et al., 2020). However, it is crucial to consider the potential losses from mineral fertilizers due to volatilization or leaching, as well as the current instability and rising costs of agricultural inputs (RESENDE et al., 2022).

Thus, using *C. procera* as green manure offers a sustainable alternative for arugula cultivation in semiarid environments, achieving an average yield of about 8.5 t ha^{-1}. When assessing the impact of green manure amounts on plant height, number of leaves, green and dry mass yields, and leaf area in each cultivation, an increasing polynomial trend was noted with rising amounts of *C. procera* biomass incorporated into the soil in both S1 and S2 (Figure 2).

The MPE findings for S1 and S2 were as follows: plant height reached 15.27 cm and 18.49 cm; leaf area index peaked at 1749.02 cm² and 2238.89 cm²; green mass yield was 5.87 t ha^{-1} and 10.47 t ha^{-1}; and shoot dry mass was 1.25 t ha^{-1} and 1.63 t ha^{-1}, respectively. The corresponding amounts of *C. procera* biomass were 67.84 t ha^{-1} and 45.15 t ha^{-1} for plant height, 82.00 t ha^{-1} and 68.14 t ha^{-1} for leaf area, 55.13 t ha^{-1} and 63.98 t ha^{-1} for green mass yield, and 67.17 t ha^{-1} and 67.39 t ha^{-1} for shoot dry mass for S1 and S2, respectively (Figure 2). However, the MPE values decreased beyond these optimal amounts of green manure. In both cultivations, the

MPE values exhibited an increasing polynomial trend up to the highest recorded values: 16.94 cm for plant height, 8.59 for number of leaves per plant, 1938.56 cm² for leaf area index, 8.45 t ha^{-1} for green mass yield, and 1.47 t ha^{-1} for shoot dry mass. The peak levels of green manure corresponding to these MPE values were 63.98, 58.09, 74.12, 63.31, and 68.95 t ha^{-1}, respectively, after which benefits decreased (Figures 2A, 2B, 2C, 2D and 2E).

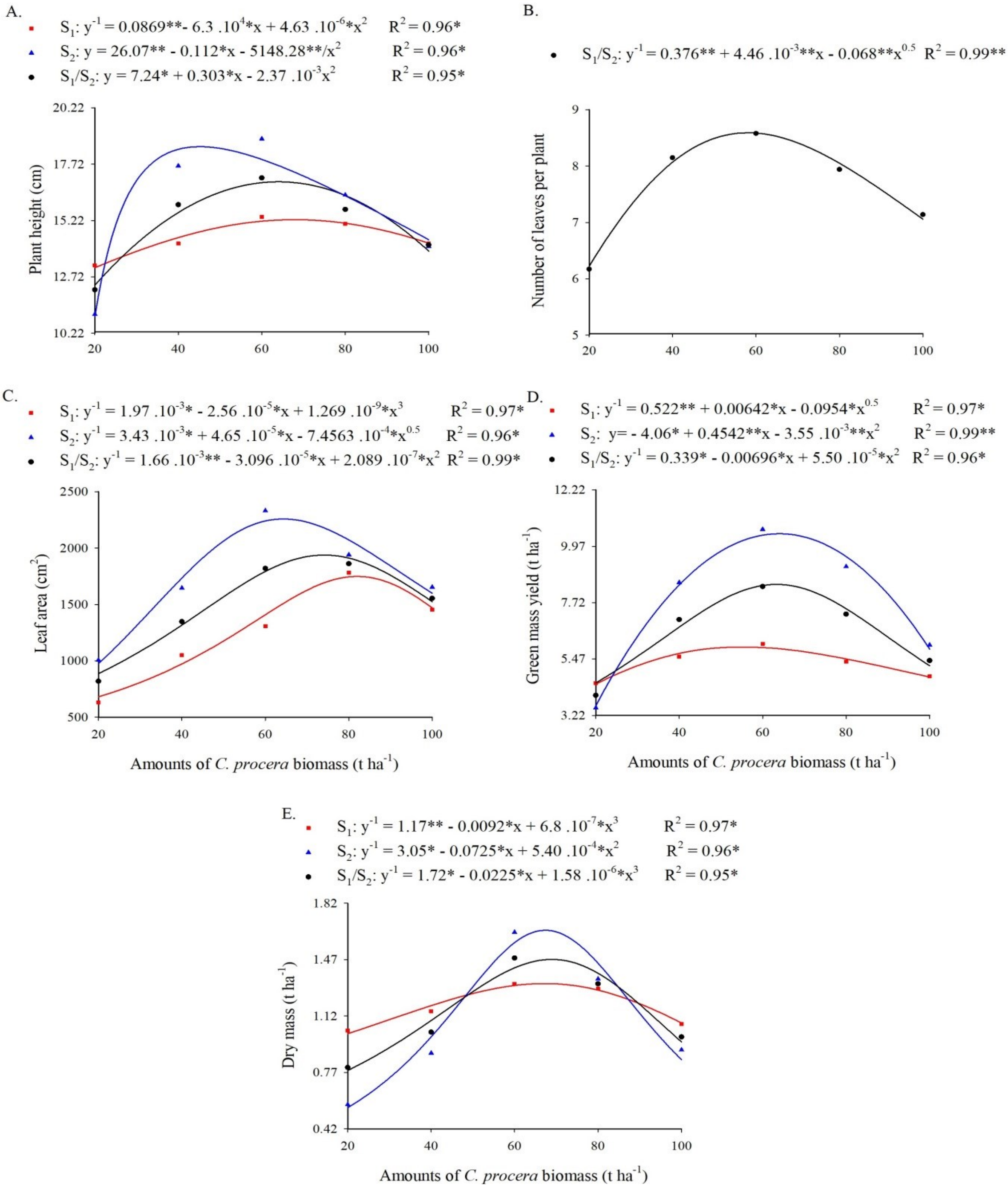


Figure 2. Plant height (A), number of leaves per plant (B), leaf area (C), green mass yield (D), and shoot dry mass (E) of arugula as a function of the *Calotropis procera* biomass amount incorporated into the soil during S_1 and S_2 seasons.

These findings underscore the efficacy of green manuring in aligning nutrient supply with crop demand, leveraging the C/N ratio of *C. procera* between 28:1 and 30:1 (FERREIRA et al., 2022). Additionally, the decline in performance beyond the peak is attributed to the "Law of Maximum," in which excess fertilizer can diminish the effectiveness of other nutrients and plant growth (SILVA et al., 2023). Similar results were observed by Silva et al. (2018), who noted that lettuce showed optimal green mass production of 18.11 t ha^{-1} with 4.39 t ha^{-1} of *C. procera*. Silva et al. (2021) also found optimal yield in carrot, 35.90 t ha^{-1}, with 47.60 t ha^{-1} of *C. procera* biomass. The effectiveness of *C. procera* as a green fertilizer was further demonstrated in an intercropping system with arugula and lettuce (ALMEIDA et al., 2015). These outcomes highlight the benefits of using *C. procera* to improve and maintain soil fertility, structure, aeration, and water retention, enhancing its chemical, physical, and biological properties, and supporting its role as a sustainable alternative to chemical fertilizers (LINO et al., 2022; SAYARA et al., 2020).

Arugula economic performance

Table 3 outlines the production costs for arugula across all treatments during distinct phases of cultivation implementation and development. These costs reflect the actual expenditures incurred by farmers throughout the production cycle. Included in these expenses are labor, repairs, and maintenance of machinery, operation of machines and implements, inputs, and the depreciation of machines, implements, and specific improvements utilized in the production process. The costs associated with green manure also cover activities such as cutting, transportation, crushing, drying, bagging, distribution, incorporation, and the electricity used for the forage machinery.

Table 4 presents the mean values of arugula's economic indicators: gross income, net income, rate of return, and profit margin. Table 3 details the production costs for arugula across various treatments throughout distinct phases of cultivation implementation and development. These costs include actual disbursements made by farmers during the production cycle, such as labor, repairs, and maintenance of machinery, operations of machines and implements, inputs, and depreciation of machines, implements, and specific improvements used in the production process. Significant interactions ($p < 0.05$) were observed between treatment factors, specifically fertilized treatments, and cultivations, for the economic indicators evaluated (Table 4).

Table 3. Economic analysis of arugula production under varying *Calotropis procera* biomass fertilization across two growing seasons.

Treatment	Season 1 and 2							
C. procera biomass content (t ha^{-1})	(VC) BRL ha^{-1}				(FC) BRL ha^{-1}		(OC) BRL ha^{-1}	(TC) BRL ha^{-1}
	(I + L)	(E)	(OE)	(MC)	(D + TF)	(FL)		
0	8,270.00	37.51	83.08	468.64	1,890.64	1,356.57	5,914.79	18,021.23
20	12,099.74	171.19	122.71	567.14	1,899.13	1,356.57	6,037.13	22,260.35
40	16,595.74	306.00	169.02	567.14	1,899.13	1,356.57	6,037.13	26,930.74
60	20,837.74	440.21	212.78	567.14	1,899.13	1,356.57	6,037.13	31,350.70
80	25,253.74	574.44	258.28	567.14	1,899.13	1,356.57	6,037.13	35,946.44
100	29,549.74	708.73	302.58	567.14	1,899.13	1,356.57	6,037.13	40,421.04
Mineral fertilizers	41,027.25	37.51	410.65	468.64	1,890.64	1,356.57	5,914.79	51,106.06

BRL – Brazilian Real (ISO 4217: BRL); VC - Variable costs; I – Inputs; L - Labor; E – Energy consumption; OE - Other expenses; MC - Maintenance and conservation; FC - Fixed costs; D – Depreciation; TF - Taxes and fees; FL - Fixed labor; OC - Opportunity costs: SLR and SFC - Sum of land rent and fixed capital rent; and TC – Total costs.

Table 4. Averages of gross income, net income, rate of return, and profit margin for control (T_c), maximum economic efficiency (MEE), green manure (T_{gm}), and mineral fertilizer (T_{mf}) treatments for arugula production during S_1 and S_2 seasons.

Treatment	Cultivation			Cultivation		
	(S1)	(S2)	(S1/S2)	(S1)	(S2)	(S1/S2)
	Gross income (BRL ha^{-1})			Net income (BRL ha^{-1})		
T_c	58,204.97cA	58,639.00cA	58,421.98c	40,183.74cA	40,617.77cA	40,400.75c
MPE	98,369.81bB	174,557.69bA	140,826.03b	70,376.45bB	142,605.70bA	111,004.64b
T_{gm}	87,602.18bB	126,286.92bA	106,943.05b	56,400.57bB	95,082.30bA	75,741.74b
T_{mf}	172,967.92aB	239,917.64aA	206,442.78a	125,524.34aB	192,474.03aA	158,999.20a
	Rate of return			Profit margin (%)		
T_c	3.22bA	3.25cA	3.24c	69.04cA	69.27bA	69.15c
MPE	3.59aB	5.98bA	4.65b	72.38bB	84.79aA	77.37b
T_{gm}	2.79bB	4.02bcA	3.41b	64.38bB	75.29bA	69.83b
T_{mf}	3.38aB	4.69aA	4.04a	72.57aB	80.22aA	77.02a

*Averages followed by the same lowercase letter within columns and uppercase within rows do not differ statistically from each other by F-test at a 5% probability level.

The economic indicators for fertilized treatments significantly outperformed the control across both seasons. Specifically, averages of gross income, net income, rate of return, and profit margin for fertilized treatments were respectively 2.4, 2.8, 1.4, and 1.1 times higher than those for the control (Table 4). Treatments with *C. procera* biomass in S_2 outperformed S_1 in rate of return and profit margin. Mineral fertilization treatment also showed superior performance in S_2 across all indicators. In contrast, the control exhibited no significant seasonal differences for all evaluated indices.

Our findings align with those observed by Souza et al. (2015), who assessed the profitability of arugula fertilized with roostertree biomass across different growing seasons. We observed that the economic performance mirrored yield patterns, with fertilized treatments (T_{gm} and T_{mf}) achieving higher yields in S_2, subsequently translating into greater profitability, particularly noted in the mineral fertilization (T_{mf}) that showed the highest averages for all studied indicators in both seasons. It is noteworthy that these calculations assumed a standardized sales value of BRL10.00 per kg for all fertilization types. If market values for organic products were higher, the financial benefits of using *C. procera* would be even greater.

Further analysis within each cultivation period showed an increasing polynomial trend in economic indicators for arugula as *C. procera* biomass amounts increased in both S_1 and S_2 (Figure 3). The maximum observed values for gross income were BRL98,369.78 in S_1 and BRL174,557.71 in S_2; for net income, they were BRL70,376.75 in S_1 and BRL142,605.66 in S_2; the rate of return reached 3.59 in S_1 and 5.98 in S_2 for each real invested; and profit margins were 72.38% in S_1 and 84.79% in S_2. These maxima corresponded to biomass additions of 61.00 and 64.00 t ha^{-1}; 51.33 and 62.05 t ha^{-1}; 34.98 and 55.61 t ha^{-1}; and 36.83 and 57.88 t ha^{-1} of *C. procera* for S_1 and S_2 respectively (Figures 3A, 3B, 3C and 3D).

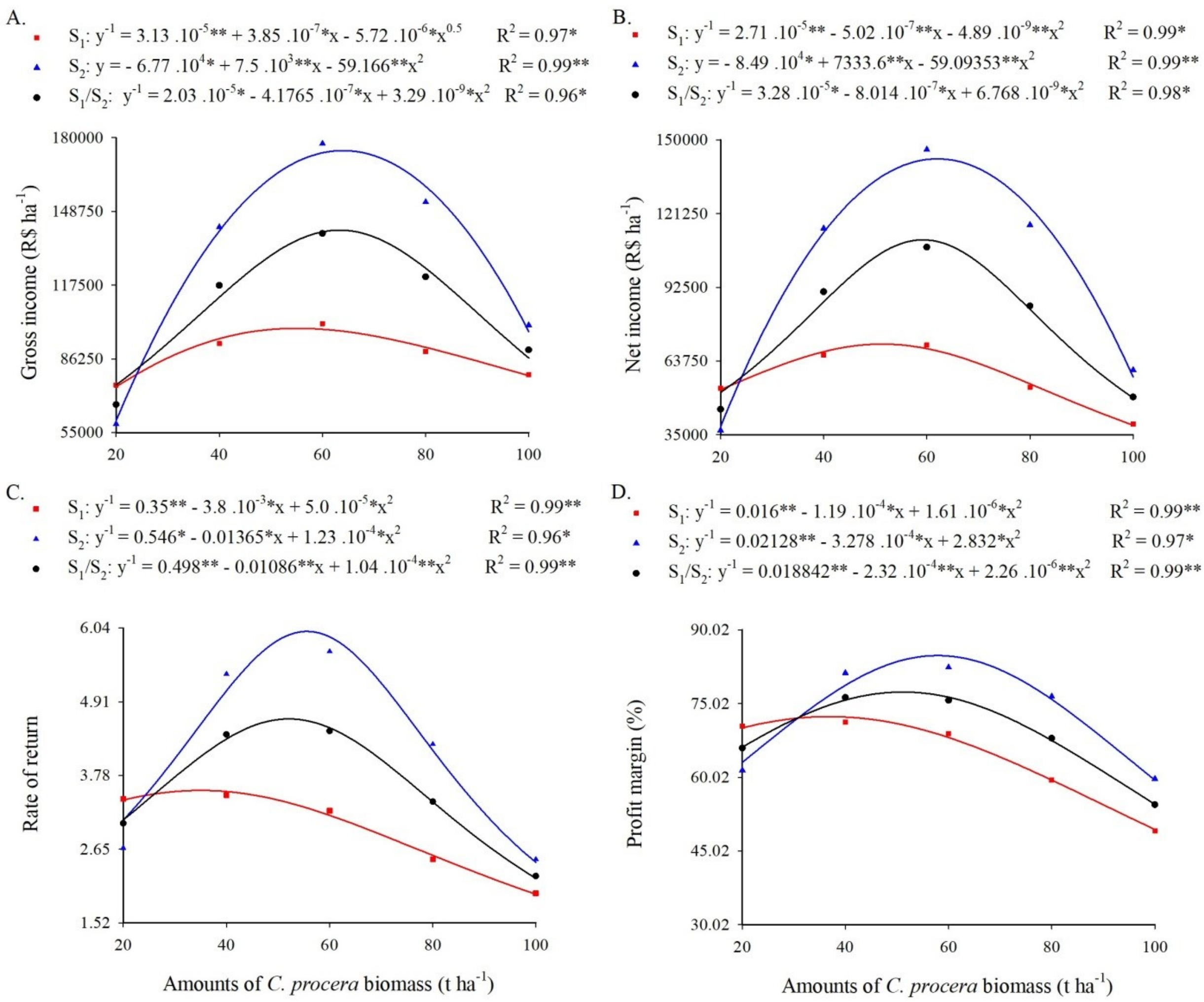


Figure 3. Gross income (A), net income (B), rate of return (C), and profit margin (D) of arugula as a function of the *Calotropis procera* biomass amount incorporated into the soil during S_1 and S_2.

This upward response is indicative of the crop's favorable reaction to fertilization, with its productivity success translating directly into economic benefits. Analysis of the maximum economic efficiencies for these indicators showed an increasing polynomial trend with the increase in green manure biomass until reaching peak values of BRL

140,826.03 ha^{-1} for gross income, BRL 111,004.64 ha^{-1} for net income, BRL 4.65 for rate of return, and 77.37% for profit margin at biomass additions of 63.31, 59.26, 55.60, and 51.12 t ha^{-1}, respectively. Beyond these points, values decreased with further increases in fertilizer amounts (Figures 3A, 3B, 3C and 3D).

Freitas et al. (2023) and Ferreira et al. (2022) also noted similar trends of economic indicators peaking before declining in studies using *C. procera* combined with *M. aegyptia* for carrot and coriander cultivations. These studies, alongside ours, highlight the financial viability of using green manuring practices with native species from the Caatinga, offering returns of BRL 4.65 for each BRL 1.00 invested on average. Silva et al. (2023), in radish cultivation, achieved maximum values of 2.94 (rate of return) and 62.55% (profit margin) using 33.18 and 33.86 t ha^{-1} of *C. procera* biomass, respectively. Similarly, Silva et al. (2024) reported a return of BRL 2.27 for each BRL 1.00 invested and a 56.63% profit margin for beet cultivation with 31.69 and 31.85 t ha^{-1} of *C. procera* biomass, respectively.

These results empower farmers to strategically select fertilization practices considering the financial and environmental cost-benefits and the market niche they aim to target, especially given the rising demand for sustainably produced foods that command higher market prices than conventionally produced alternatives (SILVA et al., 2023; FAO, 2023). Furthermore, using *C. procera* as green manure presents a feasible option for arugula production in semiarid environments due to its local availability, robust regrowth potential (3-4 cuts every 120 days), and consistent high biomass production. It also offers opportunities for employing family labor and storing it as hay, thereby reducing reliance on chemical fertilizers and cutting production costs (SILVA et al., 2023; FERREIRA et al., 2022; SANTANA et al., 2021).

CONCLUSIONS

To achieve maximum optimized productive efficiency for arugula (8.45 t ha^{-1}), 63.31 t ha^{-1} of *Calotropis procera* dry biomass had to be incorporated into the soil. The maximum optimized agroeconomic efficiency, based on a net income of BRL 111,004.64 per hectare, was achieved with 59.26 t ha^{-1} of *C. procera* dry biomass. This resulted in a rate of return of BRL 4.65 for each BRL 1.00 invested, with a profitability index of 77.37%. Utilizing *C. procera* biomass as green manure has proven to be a viable technology for arugula production in semi-arid regions.

ACKNOWLEDGEMENTS

Special thanks are due to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for their financial support of this work, and to the Plant Science Research Group of the Universidade Federal Rural do Semi-Árido, which develops technologies for growing vegetable crops on family farms.

REFERENCES

ALMEIDA, A. E. S. et al. Eficiência agronômica do consórcio alface-rúcula fertilizado com flor-de-seda. **Revista Caatinga**, 28: 79-85, 2015.

ALVES, E. S. et al. Determinação do coeficiente de cultivo para a cultura do rabanete através de lisimetria de drenagem. **Irriga**, 22: 194-203, 2017.

BECK, H. E. et al. Data descriptor: Present and future Köppen -Geiger climate classification maps at 1-km resolution. **Scientific Data**, 5: 1-12, 2018.

BELL, L.; WAGSTAFF, C. Rocket science: A review of phytochemical & health-related research in Eruca & Diplotaxisspecies. **Food Chemistry**, 1: 100002, 2019.

CARNEIRO, C. J. et al. Impacto da produção de olerícolas em sistema de base agroecológica na qualidade química do solo. **Research, Society and Development**, 11: e47211125283, 2022.

FAO. **The State of Food and Agriculture 2023:** Revealing the true cost of food to 22 transform agrifood systems. Rome. 2023.

FERREIRA, R. C. et al. Biomass use of *Merremia aegyptia* and *Calotropis procera* in coriander cultivation in semiarid environment. **Revista Caatinga**, 35: 595-605, 2022.

FREITAS, I. A. S. et al. Productivity and optimized economic efficiency of carrot roots in monocropping under green manuring. **Revista Caatinga**, 36: 572-584, 2023.

LABIMC - Laboratório de Instrumentação Meteorologia e Climatologia. **Estação Meteorológica Automática (EMA)**. Universidade Federal Rural do Semi-Árido (UFERSA), 2023. Available at: <https://siemu.ufersa.edu.br/>. Access on: Apr. 19, 2023.

LINO, F. K. K. S. et al. Agro-economic benefits in radish-lettuce intercropping under optimized green manuring and planting density. **Horticultura Brasileira**, 40: 302-310, 2022.

PEREIRA, A. G. C. et al. Respostas de cultivares de rúcula à adubação nitrogenada mineral e orgânica aplicada via cobertura. **Brazilian Journal of Development**, 6: 61008-61016, 2020.

PIMENTEL-GOMES, F. **Curso de estatística experimental**. 15. ed. Piracicaba, SP: FEALQ, 2022. 451 p.

PLIZ, A. E. et al. Parcelamento da adubação nitrogenada na cultura da rúcula em solo de textura argilosa. **Scientific Electronic Archives**, 16: 21-28, 2023.

RESENDE, A. V. et al. É hora de usar a poupança de nutrientes do seu solo. **Revista Plantio Direto Digital**, 2022: 15-23, 2022.

SANTANA, F. M. S. et al. Economic viability of beet crops using *Calotropis procera* biomass as soil fertilizer in two growing seasons. **Revista Caatinga**, 34: 846-856, 2021.

SANTOS, H. G. et al. **Sistema brasileiro de classificação de**

solos. Brasília, DF: Embrapa. 2018. 356 p.

SAYARA, T. et al. A. Recycling of Organic Wastes through Composting: Process Performance and Compost Application in Agriculture. **Agronomy**, 10: 1-23, 2020.

SILVA, E. A. et al. Productive and economic efficiency of beetroot fertilised with roostertree in a semi-arid environment. **Revista Caatinga**, 37: e12349, 2024.

SILVA, I. N. et al. Desempenho agronômico e rentabilidade econômica da alface adubada com *Calotropis procera* como adubo verde em cultivo único. **Australian Journal of Crop Science**, 12: 1573-1577, 2018.

SILVA, J. N. et al. Combinations of coriander and salad rocket cultivars in bicropping systems intercropped with carrot cultivars. **Revista Caatinga**, 30: 125-135, 2017.

SILVA, J. N. et al. Agro-economic indicators for carrot under green manure in a semi-arid environment. **Revista Caatinga**, 34: 257-265, 2021.

SILVA, J. P. P. et al. Agro-economic optimization of radish cultivation fertilized with doses of roostertree in a semi-arid environment. **Revista Caatinga**, 36: 802-813, 2023.

SOUZA, E. G. F. et al. Rentabilidade da rúcula fertilizada com biomassa de flor-de-seda em função da época de cultivo. **Revista Caatinga**, 28: 65-77, 2015.

SOUZA, E. G. F. et al. Production of lettuce under green manuring with *Calotropis procera* in two cultivation seasons. **Revista Caatinga**, 30: 391-400, 2017.

SYSTAT SOFTWARE. **TableCurve 2D** - Curve Fitting Made Fast and Easy. San Jose: Systat Software Inc., 2022.

TEIXEIRA, P. C. et al. **Manual de Métodos de Análise de Solo**. 3 ed. revista e ampliada. Brasília, DF: Embrapa, 2017. 574 p.

TRANI, P. E. et al. Alface, almeirão, agrião-d'água, chicória, coentro, espinafre e rúcula. In: TRANI, P. E. et al. (Eds.). **Hortaliças, recomendação de calagem a adubação para o estado de São Paulo**. Campinas, SP: CATI, 2018, p. 23-26.

VIEIRA, F. A. et al. Eficiência técnico-econômica do rendimento de grãos verdes de feijão-caupi fertilizado com flor-de-seda. **Revista Caatinga**, 31: 504-510, 2018.