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Assessing the potential of two alternative forage for saline semiarid regions in Brazil

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Abstract

The Brazilian semiarid region, characterized by the Caatinga biome, faces increasing challenges due to climate change, including rising temperatures, irregular rainfall, and land degradation. Limited water availability and soil salinization further constrain agricultural productivity, highlighting the need for salt-tolerant forage alternatives. This study evaluated *Moringa oleifera* and *Calotropis procera* as potential forage sources by assessing their biomass production, crude protein content, and mineral composition under saline and non-saline conditions in a greenhouse experiment. *M. oleifera* produced 14 tons/ha of shoot dry matter, maintaining higher crude protein content ($22.01 \pm 5.45\%$) compared to *C. procera* ($18.12 \pm 4.42\%$). In contrast, *C. procera* exhibited greater resilience to saline irrigation, increasing its biomass production from 3.9 tons/ha to 9.3 tons/ha, while both species yielded 8.8 tons/ha under combined saline soil and water conditions. These results highlight *M. oleifera* as a superior protein-rich forage, while *C. procera* remains a promising fiber source, particularly in highly saline environments. Future research should focus in-situ evaluations and optimizing cultivation strategies to maximize their nutritional value and forage sustainability in semiarid regions.

Keywords Biomass production, *Calotropis procera*, Forage sustainability, Livestock feed, *Moringa oleifera*, Salinity tolerance, Semiarid agriculture

1 Introduction

Semiarid regions are home to millions of people and play a crucial role in global food security, yet they are among the most vulnerable areas to climate change due to rising temperatures, erratic rainfall, prolonged droughts, and increased aridification [1–4]. These climatic shifts threaten agricultural productivity and livestock systems, particularly in the Brazilian semiarid, which spans approximately 1.182 million square kilometers, about 12% of the country's total area [5]. The region is dominated by Caatinga biome, a seasonal deciduous tropical forest and woodland (SDTFW), and is home to nearly 28 million people [1]. Water scarcity and soil degradation further exacerbate agricultural challenges, leading to reduced crop yields, increased reliance on external feed sources, and heightened vulnerability of smallholder farmers [6].



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One of the major constraints to agricultural production in the Brazilian semiarid region is salinity, which affects both soil and water resources. The region's soils are largely shallow, rocky, and nutrient-poor, with low water retention capacity due to the predominance of Precambrian crystalline rocks [7, 8]. Groundwater availability is also limited, with high salinity levels often resulting from contact with crystalline rocks and excessive evaporation rates [9, 10]. Natural soil salinization results from the weathering of minerals, capillary rise of saline groundwater, and intense evaporation rates typical of semiarid climates [11, 12]. Additionally, anthropogenic activities such as inadequate irrigation practices and poor drainage management contribute to secondary salinization, further limiting land productivity and increasing desertification risks [13, 14]. Saline soils affect plant growth by inducing osmotic stress, which reduces water uptake, and ion toxicity, which leads to physiological imbalances and decreased productivity [15–17]. The combined impact of these factors necessitates the identification of salinity-tolerant forage species that can thrive in degraded lands while maintaining nutritional value for livestock.

The livestock sector in the Brazilian semiarid region is largely dependent on native vegetation, with limited alternative forage sources available. Goat and sheep farming are particularly important in this region, accounting for over 41.4% and 31.9% of the national populations, respectively, while cattle production is less dominant due to the environmental constraints [18]. However, the seasonal availability of native forage is a significant challenge, as the dry season leads to forage scarcity, weight loss in animals, prolonged time to slaughter, and reproductive inefficiencies [19, 20]. This forage deficit often necessitates the importation of hay and straw from humid regions, increasing production costs and limiting small-scale farmers' profitability [21]. Developing locally adapted, salinity-tolerant forage crops is therefore essential to improving feed security and livestock resilience in semiarid regions. *Moringa oleifera* and *Calotropis procera* have emerged as promising alternatives for forage production in saline environments. *M. oleifera* is widely recognized for its high crude protein content, digestibility, and ability to enhance low-quality rations [22, 23], while *C. procera* is valued for its resilience to extreme environmental conditions and fiber-rich biomass [24]. Both species exhibit physiological mechanisms that enable them to tolerate high salinity, such as osmotic adjustment, antioxidant defenses, and efficient water use strategies [25, 26]. However, their potential as alternative forages in the Brazilian semiarid region remains underexplored. This study evaluates the growth performance, biomass production, and nutritional composition of *M. oleifera* and *C. procera* under saline soil and water conditions. By assessing their suitability as sustainable forage sources, we aim to provide practical insights into their integration into semiarid livestock systems.

2 Materials and methods

2.1 Species description

Calotropis procera (Aiton) W.T.Aiton (Apocynaceae) is a plant commonly known as silk flower. Although not native to Brazil, it is considered naturalized and has a wide distribution in the country, occurring in anthropic areas within the Caatinga and Cerrado biomes [27]. This shrub or sub-tree can reach up to 2.5 m in height and has a simple stem with a thick bark. Its succulent branches release white latex when cut, and the wind disperses its seeds. *Calotropis* is resistant to drought and can tolerate salinity [28], but

its biomass is reduced when subjected to saline irrigation [29]. As forage, it can be used dehydrated to feed animals, replacing corn and soy without altering meat quality [30].

Moringa oleifera Lam. (Moringaceae) is a perennial species originating from northwest India and widely distributed in Nigeria, India, Burma, Egypt, Philippines, Ceylon, and other countries, including Brazil [31]. This arboreal plant has rapid growth and can be propagated by seeds, cuttings, and seedlings [32]. *Moringa oleifera* has adaptability and resistance to long periods of drought [33] and tolerance to salinity [34]. It can be used for forage production, using leaves, fruits, and seeds as a protein and mineral source to improve animal performance [35].

2.2 Experimental design

The experiment was conducted from November to March 2019 in a greenhouse at the Federal Institute of Education, Science and Technology of Ceará— *campus* Crateús. Non-saline soils (0.426 dS m^{-1}) were collected from cultivable areas at a depth of 0–30 cm. To maintain soil structure and prevent compaction, the collected soil was mixed with 50% coarse sand. The saline soil was prepared by artificially salinizing a substrate using a sodium chloride (NaCl) solution with an electrical conductivity of 12 dS m^{-1} . After six days of exposure, the soil was removed from the solution, and the electrical conductivity of the soil saturation extract was measured at 6.00 dS m^{-1} , which was used for the saline soil treatment.

For the water factor, two levels were used: saline and non-saline water. The saline water (7.00 dS m^{-1} at 25°C) was obtained from a deep well, while non-saline water (0.306 dS m^{-1}) was sourced from the urban distribution system. To control the irrigation water volume, a water retention curve was determined for each substrate type using tensiometers, which were monitored daily to ensure adequate soil moisture. The methodology followed by [36], which is both accurate and cost-effective [37]. The greenhouse had no temperature or humidity control. It was covered with a 200-micron transparent plastic roof, while the sides were enclosed with 50% shade mesh, which reduced lateral light entry. Throughout the experiment, environmental conditions in Crateús followed the natural seasonal variations. The region's average temperature and relative humidity during the experimental period were approximately 28.12°C and 59.11%, respectively [38].

Seeds from two species were obtained from healthy plants in the city. The experiment followed a two-factor design with two treatment levels, arranged in three blocks, each containing five replications. Plants were grown in polyethylene bags ($40 \times 20 \text{ cm}$; 12.56 L) placed inside the greenhouse.

2.3 Plant growth, biomass, and chemical composition analysis

After 5 months from the planting date, plant development and biomass were measured. Shoot length and stem diameter at ground level were measured using a measuring tape (cm) and a digital caliper (mm), respectively. Plants were then collected and separated into leaf, stem, and root parts. Roots were washed in running water and sieved to avoid loss of root biomass, after which roots length was measured using a measuring tape.

All plant parts were weighed fresh using a precision scale (0.0001 g), placed in paper bags, dried in a forced air circulation oven at 65°C . For biomass measurements, drying was conducted for 48 h, whereas for nutritional analyses, samples were dried for 72 h or until reaching a constant weight [39]. After drying, the samples were weighed again,

ground, and subjected to chemical analysis of crude protein, dry matter, and mineral matter, following the methodologies recommended by [40].

Shoot dry biomass was calculated as the sum of leaf and stem dry weights, while total dry biomass included all plant parts. For crude protein and mineral matter analysis, samples were collected from five individuals per species per treatment before being processed as described.

2.4 Statistical analysis

We used a three-way analysis of variance (ANOVA) to determine differences in root, stem, leaf, shoot, and total biomass, as well as crude protein and mineral matter concentrations in leaves and roots among the two irrigation treatments, soil types, and species. To address pseudo replication (replicates used in laboratory analyses), we computed means of the samples and removed them from the analysis. In case of interactions between the three factors, we separately analyzed each species to facilitate interpretation. Data were transformed by log or square root when the assumptions of normality of residuals and homoscedasticity of variances were not met. After the ANOVA test (Appendix data), the means were compared using the Tukey test with the *emmeans* package [41]. The descriptive analysis results shows mean $\pm$ standard error. All analyses were performed using the R program [42].

3 Results

3.1 Plant biomass

The growth patterns of *M. oleifera* and *C. procera* were found to differ significantly. *M. oleifera* showed greater aerial growth (83.37 ± 4.23 cm) compared to *C. procera* (46.27 ± 1.27 cm), while *C. procera* had greater root development (37.68 ± 1.10 cm) compared to *M. oleifera* (25.41 ± 1.08 cm) (Table 1; Fig. 1a and b). The effects of saline irrigation on aerial and root development differed between the two species (Supplementary Table 1). *C. procera* did not show any significant effects on root or aerial growth when exposed to saline water (Fig. 1a and b), while *M. oleifera* had a 17.88% reduction in root length and a 21.35% reduction in aerial length when exposed to saline water.

Regarding dry biomass, *M. oleifera* had greater stem dry biomass (42.47 ± 4.75 g—Fig. 1c) and root dry biomass (44.58 ± 4.23 g—Fig. 1d) than *C. procera* (stem dry biomass – 16.13 ± 1.72 g; root dry biomass – 27.16 ± 2.54 g—Fig. 1c and d). However, water salinity affected the root and stem biomass of the two species differently (Supplementary Table 1). *C. procera* did not have its root or stem biomass affected by water salinity, while *M. oleifera* had a 49.52% reduction in root biomass and a 61.69% reduction in stem biomass under saline irrigation (Fig. 1e and f). Soil salinity resulted in a reduction in stem biomass for both species, with plants grown in saline soil (22.69 ± 3.57 g) experiencing a significant 37.82% reduction in biomass compared to non-saline soil (36.50 ± 4.12 g).

The dry leaf biomass was found to be lower for *M. oleifera* (13.90 ± 1.99 g) compared to *C. procera* (15.42 ± 1.85 g). *C. procera* had a significant increase (181.03%) in dry leaf biomass when grown under saline water (24.45 ± 3.38 g) compared to non-saline irrigation (8.70 ± 1.39 g). In contrast, *M. oleifera* reduced its dry leaf biomass by 65.66% when grown with saline irrigation (saline – 6.61 ± 2.11 g; non-saline – 19.25 ± 2.88 g) (Table 1; Fig. 1e). When comparing the shoot biomass of the two species, we found that saline water affected them in contrasting ways (Supplementary Table 1). While *M.*

Table 1 Mean and standard error for the initial development and bromatological analysis data of *Calotropis procera* and *Moringa oleifera* plant material cultivated in soils with different saline concentrations (saline (S) 6.00 dS m⁻¹ and non-saline (NS) 0.426 dS m⁻¹) and subjected to different irrigation salinities (saline (S) 7.00 dS m⁻¹ and non-saline (NS) 0.306 dS m⁻¹)

Species	Soil	Water	SH	RH	RDW	LDW	SDW	ADW
C. procera	NS	NS	50.393±1.642 ^a	36.727±2.032 ^c	21.813±3.805 ^a	10.666±2.084 ^{bc}	19.792±2.994 ^a	30.459±4.836 ^{bc}
C. procera	NS	S	46.056±3.194 ^a	42.333±3.887 ^c	39.394±7.431 ^a	25.081±5.665 ^{abc}	19.504±4.476 ^a	43.901±9.012 ^{bc}
C. procera	S	NS	47.077±2.158 ^a	35.765±1.981 ^c	23.477±4.174 ^{ab}	6.825±1.822 ^c	10.626±2.219 ^{ab}	17.451±3.541 ^c
C. procera	S	S	39.316±3.216 ^a	37.737±1.578 ^c	27.434±5.003 ^a	23.972±4.235 ^c	15.815±4.281 ^a	39.787±8.250 ^{abc}
M. oleifera	NS	NS	104.923±5.696 ^d	31.238±1.976 ^{bc}	64.490±8.592 ^b	22.155±3.841 ^{bc}	68.125±8.970 ^b	90.067±12.744 ^a
M. oleifera	NS	S	78.182±9.638 ^{cd}	22.985±2.227 ^{ab}	31.566±5.306 ^{ab}	9.677±3.181 ^{abc}	27.510±7.236 ^{ab}	37.187±9.631 ^{abc}
M. oleifera	S	NS	85.917±7.706 ^{bc}	24.292±1.843 ^a	47.407±8.441 ^a	16.237±4.304 ^{ab}	44.611±9.255 ^a	63.272±13.700 ^{ab}
M. oleifera	S	S	51.688±7.014 ^{ab}	21.917±1.525 ^{ab}	21.896±5.833 ^a	1.792±1.445 ^a	12.510±5.338 ^a	14.301±6.579 ^c
Species	Soil	Water	TDW	LMM	RMM	LCP	RCP	
C. procera	NS	NS	57.633±6.526 ^{abc}	17.940±0.412 ^{cd}	5.576±0.903 ^a	16.731±1.475 ^{ab}	7.750±0.593 ^a	
C. procera	NS	S	81.075±14.356 ^a	20.885±0.955 ^{bc}	6.097±0.668 ^a	22.575±0.775 ^a	8.819±0.419 ^a	
C. procera	S	NS	40.940±7.231 ^{abc}	14.975±0.654 ^{dc}	5.350±0.725 ^a	14.563±1.006 ^{bcd}	7.612±0.381 ^b	
C. procera	S	S	69.453±13.732 ^{abc}	22.187±0.583 ^c	5.184±0.347 ^a	18.606±0.912 ^{abc}	11.15±1.425 ^b	
M. procera	NS	NS	160.079±21.282 ^c	9.479±0.304 ^a	7.139±0.430 ^b	17.344±1.000 ^{abc}	11.019±2.400 ^a	
M. oleifera	NS	S	69.035±13.042 ^{bc}	11.116±0.172 ^a	8.168±0.369 ^b	23.800±0.694 ^{abc}	11.544±0.519 ^a	
M. oleifera	S	NS	115.609±18.826 ^{ab}	9.145±0.328 ^{ab}	6.783±0.507 ^b	18.038±1.331 ^{cd}	7.019±1.188 ^b	
M. oleifera	S	S	39.989±8.896 ^{abc}	11.208±0.665 ^{ab}	7.972±0.491 ^b	28.050±1.181 ^d	9.744±1.300 ^b	

S, Saline soil or water; NS, Non-saline soil or water; SH, Shoot Height (cm); RH, Root Height (cm); RDW, Root Dry Weight (g); LDW, Leaf Dry Weight (g); SDW, Stem Dry Weight (g); ADW, Shoot Dry Weight (g); TDW, Total Dry Weight (g); LMM, Leaf Mineral Matter (%); RMM, Root Mineral Matter (%); LCP, Leaf Crude Protein (%); and RCP, Root Crude Protein (%). Different letters represent significant differences in the tukey's mean comparison test (95% confidence)

oleifera showed a reduction in shoot dry weight when cultivated in saline water (saline -28.29 ± 6.62 g; non-saline -76.94 ± 9.45 g), *C. procera* actually had an increase in aerial dry biomass production (saline -41.55 ± 6.02 g; non-saline -23.82 ± 3.10 g) (Fig. 1f). When comparing the total dry biomass of the two species under all conditions, there were no significant differences between them, because the differences in stem, leaf, and root dry biomass were balanced out in the total dry biomass. However, there was an interaction between species and irrigation type, and *M. oleifera* had its total biomass reduced by 60.32% when grown under saline water. *C. procera* was not affected by irrigation type (Table 1; Fig. 1g).

3.2 Crude protein and mineral content of plant leaves and roots

The bromatological analysis revealed significant differences in crude protein content between the two species, particularly in leaf crude protein (LCP), while root crude protein (RCP) did not show species-specific differences (Table 1; Fig. 2a, b). *M. oleifera* exhibited higher leaf crude protein (LCP: $22.01 \pm 5.45\%$) than *C. procera* (LCP: $18.12 \pm 4.42\%$), highlighting its superior nutritional value as a forage crop. Similarly, *M. oleifera* had higher root mineral matter (RMM: $7.52 \pm 1.49\%$), compared to *C. procera* (RMM: $5.56 \pm 1.79\%$). In contrast, *C. procera* had significantly higher leaf mineral matter ($19.05 \pm 3.42\%$) compared to *M. oleifera* ($10.08 \pm 1.22\%$) (Table 1; Fig. 2c, d).

Saline irrigation had a strong positive effect on crude protein accumulation in both species. Plants irrigated with saline water had 18% more root crude protein ($10.27 \pm 3.08\%$) than those irrigated with non-saline water ($8.42 \pm 4.69\%$) (Table 1). The effect was even more pronounced for leaf crude protein, where plants under saline irrigation ($23.25 \pm 4.39\%$) had 40% higher leaf protein content compared to those receiving non-saline water ($16.60 \pm 3.82\%$) (Table 1; Fig. 2b).

The effects of soil salinity differed between species (Supplementary Table 1). In *C. procera*, leaf crude protein decreased by 15% when grown in saline soil (LCP: $16.58 \pm 3.61\%$ under saline conditions vs. $19.65 \pm 4.71\%$ in non-saline soil). However, in *M. oleifera*, soil salinity did not reduce crude protein content, suggesting a stronger tolerance to saline soil conditions in terms of protein synthesis. Additionally, saline irrigation significantly increased leaf mineral matter across both species (Fig. 2c, d). Plants irrigated with saline water ($17.98 \pm 5.42\%$) had 33% more leaf mineral matter than those irrigated with non-saline water ($13.47 \pm 4.02\%$) (Table 1; Fig. 2d). These findings reinforce the importance of irrigation management in forage cultivation under saline conditions. While *M. oleifera* proved more resilient in maintaining its protein content under soil salinity, *C. procera* demonstrated greater flexibility in adapting to different water conditions, making it a viable forage option in regions where saline irrigation is the only available water source.

4 Discussion

The Brazilian semiarid region is estimated to have an area of around 91,000 km² with saline soils, equivalent to 9.4% of the total area, and this percentage increases to 25% when only considering irrigated areas [43]. Salinity modifies soil water potentials, alters nutrient availability, and negatively affects agricultural production. The use of tolerant species is a productive alternative for areas that are already saline. *M. oleifera* and *C. procera* were found to be little affected by soil salinity, with only height and stem biomass decreasing. When considering total dry matter or shoot matter production (Fig. 1f and

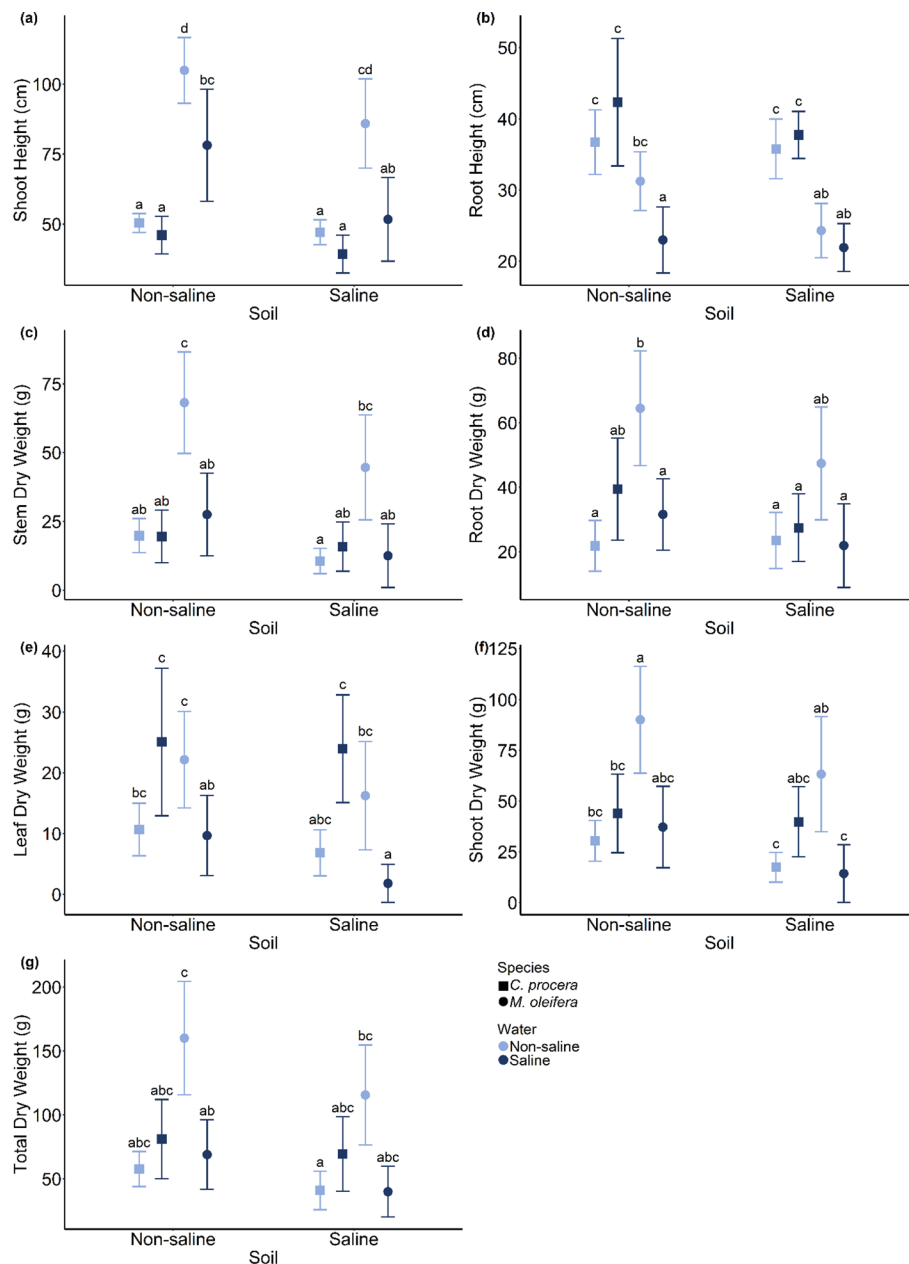


Fig. 1 Initial development of plant material from *Calotropis procera* (squared) and *Moringa oleifera* (circle) grown in soils with different salt concentrations (saline 6.00 dS m⁻¹ and non-saline 0.426 dS m⁻¹) and receiving different irrigation salinities (saline 7.00 dS m⁻¹—dark blue; and non-saline 0.306 dS m⁻¹—light blue). The graphs represent the mean and confidence interval of the data without transformation. Different letters represent significant differences in the Tukey's mean comparison test (95% confidence)

g), there were no significant differences among different soil types (saline vs. non-saline). For fodder purposes, a narrow spacing of 15 cm x 30 cm is recommended for *M. oleifera* [44], which would allow planting 222,778 plants per hectare. In saline soils, *M. oleifera* can produce up to 14 tons/ha of shoot dry matter per hectare, while *C. procera* can produce almost 3.9 tons/ha. Although there is no recommendation for the optimal planting spacing for *C. procera*, we used the same 15 x 30 cm, and studies are necessary to determine it. It is worth noting that the study employed polyethylene bags, potentially leading to an underestimation of biomass production due to bag size constraints [45].

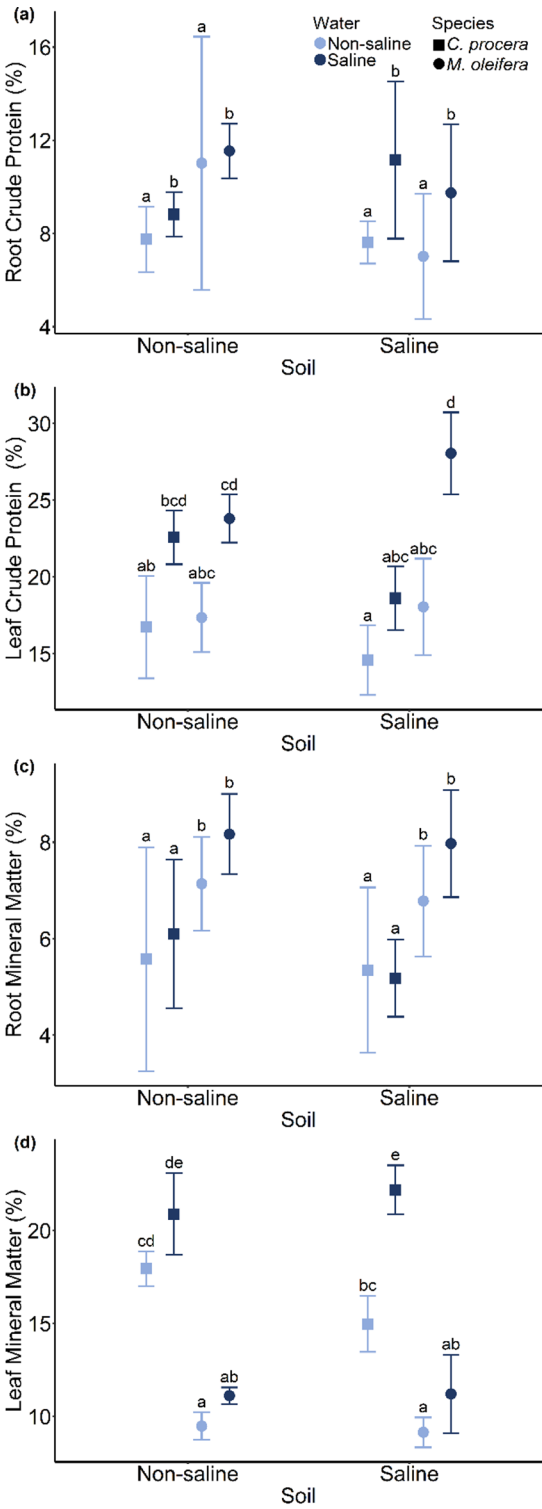


Fig. 2 Bromatological analysis of plant material from *Calotropis procera* (squared) and *Moringa oleifera* (circle) grown in soils with different salt concentrations (saline 6.00 dS m⁻¹ and non-saline 0.426 dS m⁻¹) and receiving different irrigation salinities (saline 7.00 dS m⁻¹—dark blue; and non-saline 0.306 dS m⁻¹—light blue). The graphs represent the mean and confidence interval of the data without transformation. Different letters represent significant differences in the Tukey's mean comparison test (95% confidence)

Calotropis is remarkably adaptable and maintains its productivity in severe arid conditions. This plant can survive drought, salinity, low humidity, and extreme temperatures. Despite reduced stomatal conductance, it maintains a high photosynthetic rate, which increases its water use efficiency, making it an excellent option for the Brazilian semi-arid region [46]. In fact, under saline water irrigation, the species increased its shoot dry mass production by 1.7 times and could produce 9.3 tons/ha in these conditions (Fig. 1f– Table 1). In extremely challenging conditions, such as growing under saline soils and water, the species could still produce 8.8 tons/ha of shoot dry matter. The high production of *C. procera* under stress conditions may be attributed to its strong stomatal regulation, which increases CO₂ assimilation and water use efficiency, as well as its root aquaporin expression regulation, which plays a central role in maintaining water uptake and hydraulic conductivity under saline conditions [47, 48]. Under salt stress, aquaporin expression is often downregulated to prevent excessive water loss, while selective upregulation of specific isoforms, such as PIP2;1, enhances water uptake in deep root tissues, reducing the impact of osmotic stress [49, 50]. Additionally, *C. procera* exhibits an efficient ionic regulation system, where Na⁺ and Cl⁻ accumulate in roots and leaves to maintain osmotic balance, while K⁺ levels decrease significantly in leaves under salinity, leading to a 54% reduction [51]. These physiological mechanisms allow the plant to optimize water use and maintain photosynthesis even under high salinity conditions.

Another key adaptation of *M. oleifera* under salt stress is its stomatal regulation, which plays a crucial role in maintaining water balance and optimizing photosynthesis. Stomatal closure begins within two hours of salt exposure, reducing CO₂ uptake and leading to a 43% decline in photosynthesis under 7.5 dS m⁻¹ NaCl, which reaches 95% at 15 dS m⁻¹ NaCl [52]. Despite these limitations, transpiration remains active under moderate salinity (7.5 dS m⁻¹ NaCl), likely due to cuticular water loss, but declines sharply at higher salt concentrations, restricting water uptake and growth. In addition to stomatal regulation, proline accumulation plays a significant role in *M. oleifera*'s osmotic adjustment and stress tolerance [25]. Proline functions as an osmotic regulator, stabilizing proteins and cellular structures while reducing oxidative stress. This mechanism enables the plant to maintain turgor pressure and cellular integrity under saline conditions. Furthermore, *M. oleifera* exhibits an enhanced antioxidant defense system, with increased activities of superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), which help neutralize reactive oxygen species (ROS) generated under salinity stress [26]. These physiological responses mitigate oxidative damage and contribute to the species' resilience in saline environments.

Unlike many salt-sensitive species, *M. oleifera* maintains its chlorophyll a and b content under salinity, preventing significant declines in photosynthetic capacity. However, carotenoid levels are reduced by 40–57.5%, which may impact photoprotection against oxidative damage [25]. Moreover, at moderate salinity levels (5 dS m⁻¹ NaCl), the plant maintains a balanced biomass allocation between roots and shoots, but at higher salinity (10 dS m⁻¹ NaCl), there is a shift in growth favoring root development, a common adaptation to enhance water uptake under osmotic stress [26]. These responses highlight *M. oleifera*'s ability to sustain photosynthetic function and optimize biomass distribution under saline conditions, reinforcing its potential as a forage crop in semiarid regions.

Despite these physiological adjustments, under high salinity conditions, productivity declines significantly (6.3 tons/ha vs. 17.1 tons/ha), reinforcing the need to evaluate

realistic irrigation scenarios in the semiarid region. The deep well water used in this study had a salinity of 7 dS m^{-1} , which is considered high. However, regional assessments indicate that less than 5% of the deep wells in the Brazilian semiarid region exhibit salinity levels equal to or greater than this study, while the majority (75%) have a salinity of less than 1.5 dS m^{-1} [53]. This suggests that, in most real-world conditions, *M. oleifera* may experience milder saline stress than reported here, which could allow for higher productivity than observed in this experiment.

Forage quality is a complex topic that intersects many academic areas and is perhaps the most crucial factor influencing ruminant productivity. Compared to tropical grasses such as Buffel grass (*Cenchrus ciliaris*), *M. oleifera* provides significantly higher protein content (30.3% vs. 9.16% for Buffel grass), making it an important nutritional supplement for livestock diets [54]. This high protein concentration is particularly relevant for small-scale livestock producers, who often struggle with protein deficiencies in semiarid regions. Additionally, saline irrigation increased crude protein content by 40%, reaching $23.25 \pm 4.39\%$, highlighting its ability to thrive under saline conditions without significant nutritional losses (Table 1; Fig. 2c).

Moringa is considered a good protein, mineral, and energy source, making it a convenient substitute for soybean and rapeseed meals for ruminants [22, 23]. The species enhances metabolic protein supply by supporting microbial protein synthesis in the rumen due to its high content of readily fermentable nitrogen and energy (23). Additionally, the presence of tannins and saponins in *M. oleifera* has been shown to reduce methane emissions by 12.26–12.97% by inhibiting methanogenic archaea and shifting rumen fermentation pathways toward higher propionate production [55, 56]. This suggests that *Moringa* is not only a sustainable forage option in saline environments but also a potential tool for reducing greenhouse gas emissions in livestock production systems. While *M. oleifera* serves as a superior protein supplement, *C. procera* also has potential as a fiber-rich forage source, particularly in semiarid environments where traditional forages struggle to grow. Studies have shown that *C. procera* can substitute sorghum hay to improve digestibility and energy content in animal diets, with recommendations that silk flower hay comprise up to 16.5% of lamb diets under a 1:1 roughage: concentrate ratio [24]. Previous studies indicate that crude protein content in *C. procera* typically ranges from 9 to 20%, and our study further supports this range, reporting values from 14.56 to 22.57%. Notably, saline irrigation increased crude protein levels, reaching the highest values observed (Table 1). Although its crude protein content is lower than that of *M. oleifera*, its adaptability to harsh environments and reasonable digestibility makes it an alternative forage option in areas with saline constraints. Furthermore, ensiling and haymaking can mitigate the toxic effects of latex compounds, ensuring safe inclusion in balanced ruminant diets [57, 58].

5 Conclusions

Returning to our objectives, which were to evaluate the potential of *Calotropis procera* and *Moringa oleifera* as sustainable forage sources for livestock in semiarid regions, our findings confirm that both species are viable options for production in harsh conditions such as saline soil and water scarcity, which are common in these regions. Our results showed that protein, a limiting factor for ruminant production, can be enhanced in cultivars grown in saline water. Furthermore, *C. procera* showed an increase in biomass

production under saline stress, while *Moringa oleifera* had a slight reduction in production but remained a valuable alternative forage source due to its high nutritional content.

However, some limitations must be considered. This study was conducted under controlled greenhouse conditions, which do not fully capture the variability found in field environments, including seasonal climate fluctuations, soil heterogeneity, and competition with native vegetation. Future research should focus on evaluating both species under field conditions to determine their actual productivity, persistence, and resilience when exposed to the complex interactions present in semiarid ecosystems. Additionally, there is a need for further studies on the long-term ecological implications of large-scale cultivation of *C. procera*, particularly regarding its potential invasiveness and effects on soil properties under continued saline irrigation. From a practical perspective, these species represent a valuable strategy for improving forage quality in semiarid regions, particularly during the dry season when conventional forage resources are scarce. *M. oleifera* has already been widely recognized for its ability to enhance the nutritional value of low-quality forages, while *C. procera* emerges as an option for fiber-rich forage that can sustain livestock under harsh conditions. However, the application of these species depends on technological adaptation, as haymaking and silage production are not common practices among smallholder farmers in the region. Future research should focus on developing accessible processing techniques and training programs to facilitate the adoption of these forages by local producers.

Finally, economic constraints must also be considered. While both species offer a sustainable alternative to conventional forage sources, initial investments in planting, managing, and processing them may pose challenges for small-scale farmers. Policies promoting sustainable forage adoption, combined with technical assistance programs, could play a crucial role in integrating these species into semiarid livestock systems, reducing feed dependency, and increasing resilience to climate variability. Overall, this study highlights the potential of *Calotropis procera* and *Moringa oleifera* to contribute to livestock production in semiarid regions. Their ability to withstand saline conditions and maintain nutritional value makes them valuable resources for improving forage availability and quality in regions where traditional pastures are insufficient, providing practical benefits for farmers while addressing broader global challenges in food security and climate resilience.

Supplementary Information

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Supplementary Material 1

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Author contributions

ABG and DBN conceived the idea of the study. MFS, AFP, and AGCS prepared the experimental area and, together with DBN, collected the data. ABG analyzed the data and wrote the first draft of the manuscript. MFS and ABG revised the manuscript after reviewer feedback. All authors contributed to the revision of the manuscript and approved the final version.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The plants used in this study are *Calotropis procera*, a naturalized species in Brazil, and *Moringa oleifera*, which is considered a cultivated species in the country. The seeds were sown, and the plants were cultivated by Alton B. Giroldo. The collection, cultivation, and use of these species comply with Brazilian national and local legislation. As the study does not involve genetic or cultural heritage as defined by Law No. 13,123/2015, no specific license or additional affirmation is required.

Competing interests

The authors declare no competing interests.

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