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Succulent forages sustain lamb performance and hydration without compromising thermoregulation in semi-arid feedlots

Priscila Izidro de Figueirêdo[1], Italo Marcos de Vasconcelos Morais[2], José Renaldo Vilar da Silva Filho[3], Jaíne dos Santos Amorim[3], Daniel Maia Nogueira[4], Gherman Garcia Leal de Araújo[4], Tadeu Vinhas Voltolini[4]*

[1]Universidade Federal Rural de Pernambuco – Depto. de Química, R. Dom Manoel de Medeiros s/n – 56171-900 – Recife, PE – Brasil.
[2]Universidade Federal da Grande Dourados – Depto. de Zootecnia, Rod. Dourados/Itahum, km 12 – 79804-970 – Dourados, MS – Brasil.
[3]Universidade Federal do Vale do São Francisco – Lab. de Bromatologia e Nutrição Animal, Rod. BR 407, 12, lote 543 – 56300-000 – Petrolina, PE – Brasil.
[4]Embrapa Semiárido, Rod. BR 428, km 152, Zona rural s/n – 56302-970 – Petrolina, PE – Brasil.
*Corresponding author <tadeu.voltolini@embrapa.br>

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ABSTRACT: Forage watermelon (*Citrullus lanatus* var. citroides) and spineless cactus (*Opuntia stricta*) are succulent forages with high water content, making them potential food sources for thermoregulation and performance of confined sheep in tropical environment. This study evaluated animal performance, intake and digestibility of dry matter and nutrients, water and nitrogen balances, ingestive behavior, and thermoregulatory responses of sheep fed diets with spineless cactus or forage watermelon as partial replacements for Tifton 85 hay (*Cynodon dactylon*). The treatments were: 1 – Tifton 85 hay-based diet (HAY); 2 – spineless cactus-based diet (CAC) and 3 – forage watermelon-based diet (FWM). Ten replicates per treatment were used in a completely randomized design. Male, non-castrated sheep of undefined breed, aged three months with initial body weight of 21.20 ± 2.41 kg, were used. Dry matter (DM), total carbohydrate, and neutral detergent fiber intake and digestibility were not influenced by diets. However, FWM resulted in lower crude protein intake and digestibility compared to CAC. Diets with succulent forages reduced free water intake and increased total water ingestion. Nitrogen intake, absorption, and balance were lower for FWM than CAC. Average daily gain, final body weight and feeding efficiency were also not influenced by dietary treatments. Feeding time was longer for CAC than HAY, while physiological responses remained unchanged across treatments. Including forage watermelon or cactus increased dietary water intake without negatively affecting water balance, average daily gain, final body weight, nor thermoregulation when used as partial replacements for Tifton 85 hay in feedlot sheep diets.

Keywords: *Citrullus lanatus* var citroides, forage watermelon, *Opuntia stricta* (Haw), spineless cactus, semi-arid

Introduction

Heat stress in tropical semi-arid regions reduces dry matter intake and compromises animal welfare and performance in ruminants (De K et al., 2020). Adequate water supply mitigates heat stress in ruminants by promoting thermoregulation (Kausar and Imran, 2024). Thus, adequate water supply plays a key role in mitigating the impacts of harsh environmental conditions by promoting thermoregulation through direct cooling. Succulent feeds like spineless cactus and forage watermelon improve hydration and thermal comfort in animals (Araújo et al., 2010).

Forage watermelon, *Citrullus lanatus* (Thunb.) Matsum. & Nakai var. *citroides* (L.H. Bailey) Mansf., and spineless cactus, *Opuntia stricta* (Haw.) Haw., can be considered succulent forages due to the high moisture content in their fruit and cladodes, respectively (Silva et al., 2021). The DM, crude protein (CP), and neutral detergent fiber (NDF) contents may vary depending on the cultivar or species. For spineless cactus, these values ranged from 10 to 15 % DM, 4 to 6 % CP, and 20 to 32 % NDF (Costa et al., 2009; Pessoa et al., 2013). For fresh forage watermelon, values ranged from 6.5 to 9.9 % DM, 9.4 to 21.5 % CP, and 38.4 to 52.6 % NDF, respectively (Azeredo et al., 2021; Santos et al., 2017). Therefore, these forages can significantly contribute to the supply of water and nutrients in ruminant diets (Azeredo et al., 2021; Cardoso et al., 2019; Ribeiro et al., 2022).

As regards productivity, the forage mass yield of irrigated spineless cactus cladodes can range from 388 to 763.5 t ha^{-1} at 16 months after planting (Rocha et al., 2017). The fruit yield of forage watermelon can vary from 25 to 30 t ha^{-1}, depending on soil conditions, management practices, and rainfall regime (Araújo, 2015). Despite their differing yields, these forages are productive and water-efficient in semi-arid systems (Ribeiro et al., 2021; Rocha Filho et al., 2021). It is still unclear whether succulent forages improve thermoregulation and performance in sheep under heat stress.

We hypothesized that the cladodes of spineless cactus or the fruit of forage watermelon could partially replace Tifton 85 hay in sheep diets, thereby improving water intake without impairing intake, digestibility, performance, or thermoregulation. This study aimed to evaluate performance, intake, digestibility, water and nitrogen balances, behavior, and physiological responses of sheep fed these diets.

Materials and Methods

Ethical aspects and location

All procedures were conducted in accordance with the guidelines for ethics and animal well-being and approved by the Ethics Committee on the Use of Animals (CEUA) of the Embrapa Semiárido under protocol number 03/2018.

The study was carried out at the experimental field of Embrapa Semiárido, located in the municipality of Petrolina, in the state of Pernambuco, Brazil (9°09′00″ S, 40°22′00″ W, altitude 365 m).

Animals and experimental period

Thirty non-castrated and non-defined breed lambs were used, with an initial average age of three months and 21.20 ± 2.41 kg of initial body weight (IBW), distributed in individual pens (2 × 2 m) in a covered and ventilated shed. The experimental period lasted 59 days, 10 for adaptation and 49 for data collection. During the adaptation period, each animal received the same diet as the designated treatment to ensure adequate transition and adaptation.

Treatments and experimental design

The treatments corresponded to three dietary groups: (1) HAY, Tifton-85 hay and a concentrate mixture (ground corn grain, soybean meal and mineral mix); (2) CAC, a diet incorporating spineless cactus cv. Orelha de Elefante Mexicana, along with Tifton 85 hay and concentrate; and (3) FWM, a diet including forage watermelon fruits, Tifton 85 hay and concentrate.

The experiment followed a completely randomized design with ten replicates per treatment. Although no formal power analysis was done, this sample size follows the common practice in similar small ruminant studies.

Diets

Diets were formulated according to NRC (2007) recommendations to support an average daily gain (ADG) of 200 g. Before diet formulation, all feed ingredients were analyzed for nutrient composition to ensure nutritional adequacy, and these values are presented in Table 1. Forage watermelon fruits and spineless cactus cladodes were hand-chopped and processed with a forage chopper to obtain small, uniform particles, although particle size was not formally measured. All ingredients were hand-mixed to prepare a total mixed ration. Feed was offered based on the previous day's dry matter intake, with daily adjustments to ensure approximately 10 % feed refusal.

Animals were fed a total mixed ration twice daily, at 09h00 and 15h00. Feeding amounts were adjusted daily based on the previous day's dry matter intake, with leftovers weighed each morning before feeding to maintain approximately 10 % refusals. Twice weekly, about 10 % of the total leftovers from each animal, were collected, labeled, and stored frozen.

Chemical composition

After collection, feed, leftovers, and feces samples were immediately stored at –20 °C for later analysis. Prior to laboratory analysis, samples were thawed at room temperature (approximately 25 °C) and homogenized. Subsequently, they were dried in an oven at 55 °C for 72 h, ground in a Wiley mill (1 mm sieve), and stored in sealed containers. Urine samples were stored in plastic containers under freezing conditions (–20 °C) and thawed in the same way prior to analysis.

Feed and ingredient samples were collected weekly throughout the experimental period to account for potential variations in composition. Composite samples were formed for each diet and used in the chemical analyses.

The chemical composition (Table 1) was analyzed following the methodologies recommended by AOAC (2016): DM content (method 967.03), ash (method 942.05), and CP (method 981.10). The ether extract (EE) was determined according to AOCS (2017). NDF and acid detergent fiber (ADF) and lignin were determined according to Van Soest et al. (1991). The NDF was corrected for ash and protein (NDFap) as described by Licitra et al. (1996).

Non-fibrous carbohydrates (NFC) were calculated following Detmann and Valadares Filho (2010), while total carbohydrates (TC) were estimated according to Sniffen et al. (1992). The ingredient composition (% DM) and the chemical composition of the diets are presented in Table 2.

Table 1 – Chemical composition of ingredients used in experimental diets.

Nutrient (% DM)	Ingredients (% DM)				
	Hay Tifton-85	Spineless cactus	Forage-watermelon	Corn grain (ground)	Soybean meal
DM (% as fed)	80.35	15.33	7.71	91.13	93.09
OM	93.46	84.53	87.94	98.57	93.29
Ash	6.54	15.47	12.06	1.43	6.71
CP	7.21	4.34	15.01	8.56	47.80
NDFap	63.53	17.82	30.26	13.52	13.36
ADF	32.10	9.16	23.84	4.11	9.86
EE	2.40	3.07	14.42	4.23	1.93
TC	83.85	77.11	51.72	85.78	43.56
NFC	15.11	57.53	31.28	72.26	30.20
Lignin	4.78	1.37	5.44	1.23	1.60

DM = dry matter; OM = organic matter; CP = crude protein; NDFap = neutral detergent fiber corrected for ash and protein; ADF = acid detergent fiber; EE = ether extract; TC = total carbohydrates; NFC = non-fibrous carbohydrate.

Table 2 – Participation of ingredients and chemical composition of diets containing succulent forages replacing partially Tifton 85 hay.

Ingredient (% DM)	Diet		
	HAY	CAC	FWM
Hay tifton-85	41.0	19.0	10.0
Spineless cactus	0.0	30.0	0.0
Forage watermelon	0.0	0.0	36.0
Corn grain (ground)	41.0	26.0	35.0
Soybean meal	17.0	24.0	18.0
Mineral salt[1]	1.0	1.0	1.0
Chemical composition (% DM)			
DM (%)	78.39	25.63	33.04
OM	93.57	90.86	92.94
Ash	6.43	9.14	7.06
CP	16.88	16.39	16.93
NDFap	45.54	30.42	32.72
ADF	20.38	13.27	16.15
EE	2.06	2.13	4.71
TC	75.29	72.51	65.44
NFC	29.77	40.64	30.08
Lignin	2.28	1.53	1.21

CAC = spineless cactus-based diet; FWM = forage watermelon-based diet; HAY = tifton 85 hay-based diet; DM = dry matter, OM = organic matter; CP = crude protein; NDFap = neutral detergent fiber corrected for ash and protein; ADF = acid detergent fiber; EE = ether extract; TC = total carbohydrates; NFC = non-fibrous carbohydrates. [1]Composition of mineral salt: Calcium (Ca) = 140 g kg^{-1}; Phosphorus (P) = 70 g kg^{-1}; Magnesium (Mg) = 1.320 mg kg^{-1}; Iron (Fe) =2,200 mg kg^{-1}; Cobalt (Co) = 140 mg kg^{-1}; Manganese (Mn) = 3.690 mg kg^{-1}; Zinc (Zn) = 4.700 mg kg^{-1}; Iodine (I) = 61 mg kg^{-1}; Selenium (Se) = 45 mg kg^{-1}; Sulfur (S) = 12 g kg^{-1}; Sodium (Na) = 148 g kg^{-1}; Fluoride (F) = 700 mg kg^{-1}.

Dry matter and nutrient intake and digestibility

Leftovers were collected daily before the morning feeding. Composite samples from each animal were formed weekly and stored at –20 °C until chemical analysis.

DM and nutrient intake – organic matter (OM), NDF, CP, EE, TC, and NFC – were calculated as the difference between the total feed offered daily and the daily feed refusals. DM and nutrient digestibility were assessed over five consecutive days through total fecal collection. Animals were housed in metabolic cages that allowed for separate collection of urine and feces to prevent cross-contamination. Feces were collected twice daily using specific collection bags attached to the animals, weighed, and sampled (10 % of the total excretion). Urine was collected in plastic buckets containing 100 mL of 2 N hydrochloric acid to prevent nitrogen losses. The content of total digestible nutrients (TDN) and the TDN intake were estimated according to Sniffen et al. (1992).

Water balance

Water was offered *ad libitum* and recorded twice per week. Additionally, three buckets containing water were randomly placed in the shed to assess evaporation. Free water intake (FWI) was calculated as the difference between the water supplied and water remained, after accounting for evaporation losses. Water intake via diet (WID) was determined as the difference between the water content in the feed and in the feed refusals.

Water balance was calculated using the following equations: Total water intake (TWI) = FWI + WID; total water excretion (TWE) = water excreted in the urine + water excreted in feces; water absorbed (W_{abs}) = TWI – water excreted in the urine; water retained (W_{ret}) = TWI – TWE; water balance (%WB) = (W_{ret} / TWI) × 100.

Nitrogen balance

The nitrogen content in feed, feces, and urine was determined using the Kjeldahl method (AOAC, 2016; method 981.10).

Nitrogen (N) absorption (N_{abs}) was calculated as: N_{abs} = Ingested N (N_{ing}) – Fecal N (N_{fec}); Nitrogen retained (N_{ret}) was determined according to Decandia et al. (2000): $N_{ret} = N_{ing} - (N_{fec} + N_{ur}$ (Urinary N)). The N Balance (NB) was estimated following the equation: NB (%) = $[(N_{ing} - (N_{fec} + N_{ur})) / N_{ing}] \times 100$.

Ingestive behavior and productive performance

Ingestive behavior assessments were conducted on the eighteenth and twenty-fifth days of the experimental period over a continuous 24-h period. Observations were recorded every 5 min classifying activities as feeding, rumination or idling. Total chewing time (TCT) was calculated as the sum of feeding and rumination time (RUT). The feeding efficiencies for dry matter (FEDM) and rumination efficiencies for dry matter (REDM) and feeding efficiencies of neutral detergent fiber (FENDF) and rumination efficiencies of neutral detergent fiber (RENDF) were estimated as: FEDM = DMI (dry matter intake) / TCT and FENDF = NDF ingested / TCT; REDM = DMI / RUT; and RENDF = NDF ingested / RUT (Bürger et al., 2000).

Final body weight (FBW) corresponded to the lamb's weight recorded on the last day of the experimental period. Total weight gain (TWG) was calculated as the difference between FBW and IBW. ADG was determined by dividing TWG by the number of feedlot days. Before weighing, sheep underwent a 16-h solid fasting period. Feeding efficiency (FE) was calculated as the ratio of ADG to DMI.

Physiological parameters

The physiological parameters were measured weekly in the morning (8h00) and afternoon (14h00). Rectal temperature (RT) was measured using a digital clinical thermometer inserted into the rectum. Respiratory rate (RR) was subjectively measured by a single evaluator, counting the flank movements of each animal (breath min^{-1}). Heart rate (HR) was assessed by auscultating the left side of the animal's first ribs, using a stethoscope (beat min^{-1}).

Surface temperature was measured using a digital infrared thermometer with laser sight, positioned 10 cm from the skin at four anatomical locations: head, neck, chest and flank.

Environmental parameters recorded included air temperature, black globe temperature (BGT), black globe temperature and humidity index (BGHI) and relative humidity (RH) (Table 3). These variables were monitored continuously using dataloggers equipped with an external cable connected to the black globe sensor, recording data 24 h a day. The BGHI was determined according to Buffington et al. (1981).

Statistical analysis

The data were analyzed by analysis of variance (ANOVA) using PROC GLM of the Statistical Analysis System (SAS OnDemand for Academics). Means were compared using Tukey's test at a significance level of $p < 0.05$. The following statistical model was used:

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij},$$

where: Y_{ij} = observation related to animal j subjected to diet type i; μ = overall mean; τ = fixed effect of diet type i (i = HAY, CAC, FWM); ε = random error associated with observation j in treatment i.

Results

Dry matter and nutrient intake and digestibility

Diets did not affect DMI nor OM, NDF, TC and TDN intakes ($p > 0.05$). However, CAC based-diet promoted higher NFC intake compared to both diets ($p = 0.0045$), and higher CP intake ($p = 0.027$) in comparison to FWM. On the other hand, FWM provided a greater EE intake compared to HAY ($p = 0.005$) (Table 4).

Table 3 – Environmental parameters of temperature, humidity, and thermal comfort indexes recorded during the experimental period.

Variable	Period		SEM	*p*-value
	08h00	14h00		
Environmental Temperature (°C)	30.95^{b}	34.29^{a}	0.32	< 0.0001
BGT (°C)	31.52^{b}	34.54^{a}	0.44	0.0001
THI (°C)	77.31^{b}	80.07^{a}	0.69	0.0438
BGHI (°C)	77.66^{b}	82.33^{a}	0.65	< 0.0001
RH (%)	48.23^{a}	35.18^{b}	1.24	< 0.0001

BGT = Black globe temperature; THI = Temperature and humidity index; BGHI = Black globe temperature and humidity index; RH = Relative humidity; SEM = Standard error of the mean. In the line, means followed by similar lowercase letters do not differ by the Tukey test ($p < 0.05$).

The digestibility of DM, OM, NDF, TC and NFC were not affected by the diets ($p > 0.05$). However, the HAY resulted in higher CP ($p = 0.014$) and lower EE digestibility than FWM and CAC, respectively ($p = 0.0082$) (Table 4).

Water and nitrogen balances

CAC and FWM based diets reduced FWI by 43.56 % and 64.03 %, respectively, while increasing WID compared to HAY ($p < 0.0001$). In addition, the FWM-based diet led to higher WID than the CAC-based diet. The FWM and CAC diets also promoted higher TWI than HAY ($p = 0.0003$) (Table 5).

Water balance, W_{ur} (water in urine) and TWE were not influenced by the diets ($p > 0.05$). However, the CAC-based diet resulted in higher W_{fec} (water in feces) ($p < 0.0001$), W_{abs} ($p < 0.0001$) and W_{ret} ($p < 0.001$) compared to other treatments (p-valor) (Table 5).

Diets did not influence N_{fec} and N_{ur} ($p > 0.05$). However, HAY and CAC resulted in higher NB ($p = 0.019$), N_{ret} ($p = 0.0025$) than FWM. Additionally, CAC increased N_{ing} ($p = 0.027$) and N_{abs} ($p = 0.024$) compared to FWM (Table 5).

Productive performance and ingestive behavior

The IBW, FBW, TWG, ADG and feeding efficiency were not influenced by diets ($p > 0.05$) (Table 6), with average values of 21.20 kg, 31.44 kg, 10.24 kg, 209.03 g d^{-1} and 0.21 kg gain kg DM $ingested^{-1}$, respectively.

Table 4 – Nutrient intake and digestibility of lambs fed diets containing succulent forages replacing partially Tifton 85 hay.

Variable (kg d^{-1})	Diet			SEM	*p*-value
	HAY	CAC	FWM		
Intake (% DM)					
DM (% as fed)	0.91	1.09	1.01	0.05	0.054
OM	0.85	0.99	0.93	0.05	0.127
NDF	0.32	0.27	0.28	0.02	0.273
CP	0.14^{ab}	0.15^{a}	0.11^{bc}	0.01	0.027
EE	0.01^{b}	0.02^{ab}	0.04^{a}	0.006	0.005
TC	0.57	0.60	0.55	0.04	0.743
NFC	0.24^{b}	0.32^{a}	0.23^{b}	0.02	0.0045
TDN	0.50	0.56	0.58	0.05	0.469
Digestibility coefficient (% DM)					
DM	72.66	74.28	75.11	2.45	0.775
OM	76.15	78.15	77.30	2.22	0.816
NDF	62.44	52.03	56.66	2.28	0.306
CP	74.75^{a}	71.99^{ab}	63.23^{b}	2.69	0.014
EE	46.16^{b}	66.29^{a}	58.21^{ab}	4.22	0.0082
TC	71.95	71.52	71.87	3.22	0.995
NFC	62.44	52.03	56.66	4.69	0.306

CAC = spineless cactus-based diet; FWM = forage watermelon-based diet; HAY = tifton 85 hay-based diet; DM = dry matter; OM = organic matter; CP = crude protein; EE = ether extract; TC = total carbohydrates; NFC = non-fibrous carbohydrates; TDN = total digestible nutrients; SEM = Standard error of the mean. In the line, means followed by similar lowercase letters do not differ by the Tukey test ($p < 0.05$).

Diets did not influence rumination time, idle time, total chewing time, FENDF and RENDF ($p > 0.05$). However, feeding time was higher for the HAY diet compared to CAC ($p = 0.027$). The FWM diet increased REDM compared to the other diets ($p < 0.0001$), while CAC resulted in higher FEDM than HAY and FWM ($p = 0.0007$) (Table 6).

Physiological responses

The highest environmental temperatures (34.29 °C), BGHI (82.33 °C), and lowest RH (35.18 %) were recorded in the afternoon, while the thermal comfort zone for lambs is up to 25 °C. Temperatures reaching 35 °C during the afternoon is considered critical (Van Wettere et al., 2021). Relative humidity was low in both the morning and afternoon, and the BGHI indicated a condition of thermal risk to the animals in the afternoon ($p < 0.0001$) (Table 3).

The respiratory rate, heart rate, rectal temperature and body surface temperature during the morning or afternoon were not influenced by the diets evaluated ($p > 0.05$) (Table 7).

The respiratory rate observed with the FWM diet in the morning, as well as during the afternoon for all evaluated treatments indicated a moderate to high level of stress (McManus et al., 2015; Silanikove, 2000). Heart rates in both the morning and afternoon were higher than the values considered normal, except for HAY in the morning. Rectal temperatures, however, remained within the normal range (Marai et al., 2007).

Table 5 – Water and nitrogen balance in lambs fed diets with partial replacement of Tifton 85 hay by succulent forages.

Variable (kg d^{-1})	Diet			SEM	*p*-value
	HAY	CAC	FWM		
FWI	3.03^a	1.71^b	1.09^b	0.22	< 0.0001
WID	0.25^c	3.24^b	3.78^a	0.13	< 0.0001
TWI	3.28^b	4.95^a	4.88^a	0.28	0.0003
Wur	0.94	0.97	1.49	0.19	0.072
Wfec	0.40^b	0.79^a	0.38^b	0.06	< 0.0001
TWE	1.34	1.76	1.86	0.20	0.157
Wabs	2.34^c	3.98^a	3.39^b	0.17	< 0.0001
Wret	1.94^c	3.19^a	3.01^b	0.16	< 0.001
WB (%)	59.08	64.21	63.18	2.53	0.330
Nitrogen balance (g d^{-1})					
Ning	21.85^{ab}	23.40^a	17.95^b	1.38	0.027
Nur	2.81	2.58	2.66	0.40	0.920
Nfec	5.37	5.78	6.32	0.49	0.410
Nabs	16.47^b	17.62^{ab}	11.63^c	1.15	0.024
Nret	13.67^a	15.05^a	8.98^b	1.16	0.0025
NB (%)	61.60^a	64.27^a	49.05^b	1.63	0.019

CAC = spineless cactus-based diet; FWM = forage watermelon-based diet; HAY = tifton 85 hay-based diet; FWI = free water intake; WID = water intake via diet; TWI = total water intake; W_{ur} = water in urine; W_{fec} = water in feces; TWE = total water excretion; W_{abs} = water absorbed; Wret = water retained; WB = water balance; N_{ing} = ingested nitrogen; N_{fec} = fecal nitrogen; N_{ur} = urinary nitrogen; N_{ret} = nitrogen retained; NB = nitrogen balance; SEM = standard error of the mean. In the line, means followed by similar lowercase letters do not differ by the Tukey test ($p < 0.05$).

Discussion

Our hypothesis that spineless cactus or forage watermelon could replace tropical grass hay in diets for feedlot sheep was supported in part. Both succulent forage-based diets led to a similar productive performance, comparable intake and digestibility for

Table 6 – Productive performance, ingestive behavior, and feeding and rumination efficiency of lambs fed diets with succulent forages replacing Tifton 85 hay.

Variable	Diet			SEM	*p*-value
	HAY	CAC	FWM		
IBW (kg)	21.23	21.38	20.98	0.44	0.936
FBW (kg)	29.89	33.05	31.38	0.69	0.179
TWG (kg)	8.66	11.67	10.40	0.58	0.104
ADG (g)	176.70	238.20	212.20	0.01	0.102
FE (kg gain kg DM ingested^{-1})	0.19	0.22	0.21	0.02	0.580
Activity (min d^{-1})					
Feeding time	257.75^a	203.23^b	232.50^{ab}	13.44	0.027
Rumination time	390.75	347.75	402.75	20.81	0.164
Idle time	762.25	860.00	777.50	30.24	0.066
TCT	648.50	551.00	635.25	29.83	0.059
Feeding efficiency					
FEDM (g DM min^{-1})	3.59^b	5.55^a	4.43^b	0.32	0.0007
FENDF (g NDF min^{-1})	1.27	1.38	1.22	0.11	0.59
Rumination efficiency					
REDM (g DM min^{-1})	2.36^c	3.31^b	4.10^a	0.21	< 0.0001
RENDF (g NDF min^{-1})	0.84	0.81	0.69	0.07	0.780

CAC = spineless cactus-based diet; FWM = forage watermelon-based diet; HAY = tifton 85 hay-based diet; IBW = Initial body weight; FBW = Final body weight; TWG = Total weight gain; ADG = Average daily weight gain; FE = Feeding efficiency; TCT = Total chewing time; FEDM = feeding efficiency of dry matter; FENDF = feeding efficiency of neutral detergent fiber; REDM = rumination efficiencies of dry matter; RENDF = rumination efficiency of neutral detergent fiber; DM = dry matter; NDF = neutral detergent fiber; SEM = Standard error of the mean. Average followed by lowercase letters in line differs by Tukey test ($p < 0.05$).

Table 7 – Physiological responses of lambs fed diets with succulent forages replacing Tifton 85 hay during morning and afternoon periods.

Variable	Diets			SEM	*p*-value
	HAY	CAC	FWM		
Respiratory rate (breath min^{-1})					
Morning	59.43	60.07	65.25	1.94	0.42
Afternoon	74.27	75.80	76.20	2.96	0.96
Heart rate (beat min^{-1})					
Morning	105.33	114.23	111.28	1.99	0.18
Afternoon	126.27	136.40	139.60	2.18	0.08
Rectal temperature (°C)					
Morning	38.70	38.56	38.75	0.07	0.56
Afternoon	39.04	38.96	39.71	0.07	0.41
Body surface temperature (°C)					
Morning	32.31	32.25	32.15	0.09	0.77
Afternoon	34.82	34.71	34.78	0.06	0.75

CAC = spineless cactus-based diet; FWM = forage watermelon-based diet; HAY = Tifton 85 hay-based diet; SEM = Standard error of the mean. Average followed by lowercase letters in line differs by Tukey test ($p < 0.05$).

most nutrients and increased total water ingestion and water ingestion via diet. However, thermoregulatory responses were not influenced by the diets.

The similar productive performance observed across diets was attributed to comparable dry matter and nutrient intake and digestibility, indicating that succulent forage-based diets provided equivalent nutrient input and utilization compared to the hay-based diet. Exceptions in nutrient intake were observed for NFC and CP, which were higher for the CAC compared to FWM, and EE, which, in turn, was higher for FWM compared to HAY. The increased NFC intake from the CAC is attributed to its higher NFC content as spineless cactus contained greater NFC levels than FWM fruits and Tifton 85 hay.

The lower CP intake and digestibility, as well as the higher EE intake for the FWM diet, were due to the presence of seeds. Seeds in forage watermelon fruit introduce variability in protein and fat contents (Ribeiro et al., 2022). A reduction in CP intake and digestibility may result from feed selection by sheep, leaving a higher proportion of seeds in the leftovers, as well as the lower digestibility of seeds compared to other fruit components, leading to increased N excretion in feces. Similarly, the higher EE levels in the FWM diet contributed to the greater EE intake observed compared to other diets.

Despite the reduction in CP intake and digestibility for FWM, the observed values for all three diets were sufficient to support the level of productive performance achieved. Additionally, diets promoted similar TDN intake.

All diets evaluated provided a positive water balance for lambs, although the source of ingested water varied. The lower DM content of FWM and CAC diets compared to HAY resulted in greater WID and, conversely, higher FWI for the HAY diet. Water ingestion via diet accounted for 65 % and 77 % of total water ingested by sheep fed CAC and FWM diets, respectively, compared to only 8 % for the HAY diet.

The higher water excretion W_{fec} observed for the CAC diet is likely due to intrinsic compounds such as oxalates and minerals, which contribute to increased water ingestion and excretion. Oxalates enhance intestinal osmolality, thereby increasing water excretion through feces (Silva et al., 2022). Conversely, the main route of water excretion for sheep fed the FWM diet was via urine, which reflects the excretion of water-soluble metabolic products.

The higher CP intake observed for the CAC resulted in greater N_{ing} compared to FWM, while improved digestibility led to higher N_{abs} and N_{ret} for the CAC diet. Although the FWM diet showed lower N retention, the positive NB observed for all diets indicated an adequate N supply. Similar productive performance, with an ADG of 209.03 g d^{-1}, supports the comparable nutrient inputs provided by all diets. Furthermore, the ADG responses observed aligned with the expected productive performance based on NRC (2007) requirements.

While DMI was similar across diets, animals fed the HAY diet required more feeding time compared to those on the CAC diet, resulting in increased FEDM for CAC. In contrast, the greater REDM for FWM is attributable to the extended rumination time associated with this diet.

Environmental and thermal parameters indicated that lambs experienced conditions above the thermal comfort zone in the afternoon, reaching medium-high stress levels. During the afternoon, the BGHI exceeded the thermal comfort zone for lambs (Ferreira et al., 2023; Silva et al., 2019), indicating that animals activated their thermoregulatory mechanisms to maintain body temperature.

Despite this, rectal temperatures remained within the normal range. The inclusion of succulent ingredients in diets was insufficient to improve thermal comfort indices, which can be related to the unrestricted access for water drinkers in all treatments.

However, under conditions of limited water availability, the use of succulent forages such as forage watermelon and spineless cactus could become critical. These ingredients contributed significantly to the animals' total water intake, and most of this water came directly from the diet, indicating a potential survival advantage in water-restricted environments. Moreover, the increased water retention observed in animals fed these forages suggests more efficient internal water use, even though no significant differences were detected in TWE.

Forage watermelon or cactus, used as succulent forages in diets for feedlot sheep increase dietary water intake and total water ingestion, without negatively affecting water balance, average daily gain, final body weight, ingestive behavior or metabolic and physiological responses when partially replacing Tifton 85 hay.

These findings underscore the potential of succulent forage-based diets to sustain productive performance for feedlot sheep while promoting water conservation. Additionally, they reinforce the important role of cactus in diets for sheep for supporting dry matter and nutrient intake, and dietary water ingestion. Furthermore, forage watermelon fruit is presented as a viable alternative feed resource for sheep production systems in drylands.

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Authors' Contributions

Conceptualization: Figueirêdo PI, Araújo GGL, Voltolini TV. Data curation: Voltolini TV. Formal analysis: Figueirêdo PI, Morais IMV, Silva Filho JRV, Amorim JS, Nogueira DM, Araújo GGL, Voltolini TV. Funding acquision: Voltolini TV. Investigation: Figueirêdo PI, Morais IMV, Silva Filho JRV, Amorim JS, Nogueira DM, Araújo GGL, Voltolini TV. Methodology: Figueirêdo PI, Morais IMV, Silva Filho JRV, Amorim JS, Nogueira DM, Araújo GGL, Voltolini TV. Project administration: Voltolini TV. Supervision: Araújo GGL, Voltolini TV. Writing – original draft: Figueirêdo PI, Morais IMV, Silva Filho JRV, Amorim JS, Nogueira DM, Araújo GGL, Voltolini TV. Writing – review and editing: Figueirêdo PI, Morais IMV, Silva Filho JRV, Amorim JS, Nogueira DM, Araújo GGL, Voltolini TV.

Conflict of interest

The authors declare that there is no conflict of interest.

Data availability statement

Data will be made available upon request from the authors.

Declaration of use of AI Technologies

AI technologies or supported applications and programs were not used in the creation of the text and the calculations made.

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