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Characterisation and Recovery of Minerals in Silages of Sorghum IPA 2502 Irigated with Different Leaching Fractions of Brackish Water

Fleming Sena Campos [1,*], Gherman Garcia Leal de Araújo [2], Welson Lima Simões [2], Thieres George Freire da Silva [3], Miguel Júlio Machado Guimarães [4], Cleyton de Almeida Araújo [5], Amélia de Macedo [5], Getúlio Figueiredo de Oliveira [5], Tiago Santos Silva [6], Anderson de Moura Zanine [1], Daniele de Jesus Ferreira [1], Hactus Souto Cavalcanti [1] and Glayciane Costa Gois [5]

1 Department of Animal Science, Federal University of Maranhão, Chapadinha 65080805, Brazil
2 Embrapa Semiarido, Petrolina 56302970, Brazil
3 Postgraduate Program in Plant Production, Academic Unit of Serra Talhada, Federal Rural University of Pernambuco, Serra Talhada 56909535, Brazil
4 Federal Institute of Education, Science and Technology of Maranhão, São Raimundo das Mangabeiras 65840000, Brazil
5 Department of Animal Science, Federal University of São Francisco Vale, Petrolina 56304917, Brazil
6 Instituto Federal de Educação, Ciência e Tecnologia do Sertão Pernambucano, Ouricuri 56200000, Brazil
* Correspondence: flemingcte@yahoo.com.br

Abstract: The objective of this study was to evaluate the characteristics and recovery of minerals in silages of sorghum cv. IPA 2502 irrigated with different leaching fractions of brackish water. Sorghum cultivation was carried out in the field in a randomised block design, with four replications and four irrigation leaching fractions (0%, 5%, 10%, and 15%). From the harvested plant material, five silos per treatment, with five repetitions, were arranged in a completely randomised design for ensiling. Leaching fractions did not alter the levels of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur in sorghum. The sodium content showed a quadratic response to the leaching fractions, which was also observed for iron, manganese, and chloride. In silage, an increasing linear effect was found for nitrogen, whereas for phosphorus, potassium, and sulfur, the contents were reduced with the addition of the leaching fraction. The contents of copper, iron, zinc, and chloride in silages responded in a quadratic way. The use of brackish water, especially the 15% leaching fraction, in the cultivation of sorghum enhances the mineral contents and the recovery of some macro- and micro-nutrients after the ensiling process.

Keywords: macrominerals; mineral retention; *Sorghum bicolor*

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1. Introduction

Alteration of the hydrological cycle due to climate changes affects the water regime [1] and promotes an imbalance in freshwater distribution [2]. These modifications directly affect the production of forage plants, leading to a reduction in the carrying capacity, seasonality of animal production, and vulnerability of the production chain. Some authors [3] estimate that the Brazilian Northeast region holds about 100,000 water wells, with some level of salinity and average flow rates of approximately 2000 L/h, demonstrating the potential for their use in the irrigation of forage plants.

Irrigation with saline water is a feasible practice for forage production and does increase plant yields compared to rainfed systems [4], ensuring food safety for animal production based on roughage, thereby enhancing animal performance. Nonetheless, the salinity of water and/or soil impairs the development of plants sensitive to salt stress, affecting physiological and metabolic processes [5]. Under this cultivation condition, the nutritional profile of forage plants can be modified because of the antagonism and synergism effects of minerals on soil and plants [6], which may affect the accumulation and the intra- and extra-cellular dynamics of minerals.

Another effect of the use of brackish water is the accumulation of minerals in the superficial soil layers [7]. However, soil damage may be prevented through over-irrigation, where the water requirement of the crop is supplied with a surplus based on evapotranspiration (i.e., leaching fraction). This ensures a partial leaching of minerals/salts to deeper layers of the soil, facilitating proper plant growth [8].

Fermentative processes are essential to obtain high-quality silage, and the crop forage must have some features that facilitate the acidification of the ensiled biomass, such as suitable contents of soluble carbohydrates and dry matter as well as a low buffering capacity [9]. Minerals act as the main buffer agents on the medium, along with nitrogen compounds [10]. This reaction occurs because of the complexation of minerals with organic acids produced by lactic bacteria [10], resulting in silage with a poor quality. In this sense, it should be considered that fermentation exerts some effects on the mineral content prior to ensiling and after the fermentation period.

Sorghum (*Sorghum bicolor* L.) is a tropical grass that responds to irrigation and fertilisation and is tolerant to salt stress. According to a previous study, high leaching fractions cause linear increases in the height, total leaf area, and water use efficiency in sorghum [8]. Gois et al. [11], evaluating the leaching fractions of sorghum for silage production, reported a decrease in the dry matter content, mainly due to the accumulation of minerals in the plant; excess water resulted in increased moisture when the leaching fractions were higher.

Among the sorghum varieties, IPA2502, also termed "sweet sorghum", stands out as it does not contain tannins and can be used in grain and silage production. However, it is mainly used in silage (milky/pasty grain + green mass), but when used for grain production, after harvesting, it can be used as pasture for animals or for the production of hay.

It is important to understand the effects of the leaching fraction of brackish water on sorghum for silage production, especially regarding impacts on the composition and recovery of minerals after the ensiling process. This allows an understanding of the alterations of minerals of the forage sorghum silage under salt stress and the mineral losses during fermentation, with the aim to subsidise forage production and preservation actions in semiarid environments. In this context, we determined the mineral composition of sorghum IPA 2502 and its silage, irrigated with different leaching fractions of brackish water.

2. Materials and Methods

2.1. Study Area, Experimental Design, and Methodology

The experiment was carried out at the Caatinga Experimental Field, Embrapa Semiárido, Petrolina (latitude 9°8′9′′ S, longitude 40°18′34′′ W; 373 m above sea level), state of Pernambuco, Brazil. According to the Köppen classification, the climate is BSh, semiarid, with a rainy period between January and April. During the experiment, the relative humidity and average air temperature were 56% and 26.2 °C, respectively. The maximum daily evapotranspiration was 6.7 mm, with an average of 4.6 mm day^{-1}. Rainfall events totaled 43 mm at the end of the experiment, with an average of 2.35 mm day^{-1}.

Sorghum of the cv. IPA 2502 was sown in an experimental area formed by five rows 5 m in length spaced at 0.5 m, totaling 12.5 m^2 (5 × 2.5 m). The useful plot was composed of the three central rows without the initial and final meters of each row, totaling 4.5 m^2.

The sorghum was grown in the field, arranged in a randomised block design, composed of the sorghum variety IPA 2502 irrigated with saline water with four leaching fractions (0%, 5%, 10%, and 15%) and four replications. Water was applied daily, based on the crop evapotranspiration (ETc), by a surface drip system with a flow rate of 1.6 L h^{-1} and a nominal diameter of 16 mm; the emitters were spaced 0.30 m apart.

After all plots were below field capacity, which accounts for the soil's maximum water retention capacity, irrigation was initiated. From this point on, the FAO approach [12] was used to determine the irrigation water depth based on the crop evapotranspiration measurements made during the interval between irrigations. For this, the dual Kc methodology was employed, with basal Kc values of 0.15, 0.95, and 0.35, respectively, for the beginning, middle, and end of cycle phenological phases, in accordance with the water application efficiency and tested leaching fractions. The equation is as follows:

$$Di = [((ETo \times Kc \times Kl) - P)/Ef] \times (1 + FL) \quad (1)$$

where Di is the irrigation water depth (mm), ETo is the evapotranspiration measured in the irrigation period (mm), Kc is the crop coefficient, Kl is the coefficient of localised irrigation, P is the precipitation measured in the period (mm), Ef is the irrigation system efficiency (0.9), and FL is the applied leaching fraction.

2.2. Soil Analysis

The soil of the experimental area was classified as Acrissol (WRB/FAO), with a flat relief and a medium texture [13]. Table 1 shows the chemical and physical soil properties.

Table 1. Soil chemical and physical properties.

Sample (cm)	pH	K^+	Na^{2+}	Ca^{2+}	Mg^{2+}	Al^{3+}	CEC	SB	H + Al
					cmol dm^{-3}				
0–20	4.60	0.23	0.27	1.60	0.60	0.05	4.20	2.70	1.50
20–40	5.70	0.16	0.68	1.40	0.60	0.00	5.60	2.80	2.70
40–60	5.00	0.15	1.12	2.40	1.50	0.20	7.70	5.20	2.50
60–80	4.50	0.11	1.40	2.80	2.20	0.15	8.80	6.50	2.30
80–100	4.50	0.08	1.18	3.20	2.00	0.05	8.70	6.50	2.30
Sample (cm)	P	Cu	Fe	Mn	Zn	EC	V	Total C	
			mg dm^{-3}			m Scm^{-1}	%	g kg^{-1}	
0–20	6.14	1.07	21.40	18.20	4.54	1.33	64.00	4.60	
20–40	1.22	1.65	23.00	14.60	3.13	2.20	50.90	4.10	
40–60	0.55	1.49	8.50	12.90	2.07	2.41	67.40	3.70	
60–80	1.69	1.37	6.00	7.00	2.05	2.50	74.30	2.30	
80–100	0.21	1.18	9.50	8.10	2.82	2.60	74.20	2.10	

pH = Hydrogenionic potential; K^+ = Exchangeable potassium; Na^+ = Exchangeable sodium; Ca^{2+} = Exchangeable calcium; Mg^{2+} = Exchangeable magnesium; Al^{3+} = Exchangeable aluminum; CEC = cation exchange capacity; SB = Sum of bases; H + Al = Potential acidity; P = Available phosphorus extracted by Mehlich-1; Cu = Copper available; Fe = Iron available; Mn = Manganese available; Zn = Zinc available; EC = Electrical conductivity; V = base saturation; Total C = Total carbon.

2.3. Brackish Water

The properties of the water used for irrigation, collected weekly during the experiment, are listed in Table 2. The water used for irrigation was identified as C4S1, i.e., with a high salinity, low sodium content, and moderate hardness (75–150 mg/L) based on calcium carbonate [14].

Table 2. Chemical analysis of brackish water used for irrigation during the experimental period.

pH	EC	Ca^{2+}	Na^+	Mg^{2+}	K^+	Cl^-	$SO_4{}^2$	$CO_3{}^2$	HCO_3	SAR	TH
	ds/m					mmol L^{-1}					mg L^{-1}
7.37	4.19	15.83	14.80	14.49	0.52	55.79	4.26	4.30	4.25	3.80	140.65

pH = Hydrogenionic potential; EC = Electrical conductivity; Ca^{2+} = Exchangeable calcium; Na^+ = Exchangeable sodium; Mg^{2+} = Exchangeable magnesium; K^+ = Exchangeable potassium; Cl^- = Chlorides; $SO_4{}^2$ = Sulfates; $CO_3{}^2$ = Carbonates; HCO_3 = Bicarbonate; SAR = Sodium adsorption ratio; TH = Total Hardness.

Irrigation was carried out with saline water from underground wells with a depth of 70 m and a flow rate of 1500 L per hour. The water was applied based on crop evapotranspiration (ETc), providing 0, 5, 10, and 15% of ETc, which was met by reference evapotranspiration (ETo) and crop coordinates. The sorghum was irrigated with brackish water three times a week at 8 am (Monday, Wednesday, and Friday).

2.4. Sorghum Harvesting and Silaging

Sorghum was harvested 101 days after the cultivation of the first cycle, when the grains in the central portion of the panicle were pasty to floury. Forage harvesting was performed manually at 0.10 cm from the ground, with subsequent fractioning of the plant material in sizes from 2 to 2.5 cm. The material was homogenised and ensiled in polyvinyl polychloride silos with a diameter of 100 mm and a height of 500 mm, with a Bunsen valve. The material was compacted with wooden sockets, placing an average of 2 kg of fresh forage per silo, according to a density of 500 kg m^{-3}. From the harvested plant material, 5 silos per treatment, that is, 20 units, were arranged in a completely randomised design for ensiling. Approximately 1 kg of sand was placed at the bottom of the experimental mini-silos; cotton was used to prevent the forage from being exposed to the sand, allowing the effluent to drain. Silos were opened after 90 days, and the ensiled material at 10 cm from both ends was discarded.

2.5. Mineral Composition of Sorghum and Silage and Nutrient Recovery

To obtain minerals (macro- and micro-nutrients), the samples of the fresh plant and silage were pre-dried and ground. Subsequently, the material was subjected to sulphuric digestion to determine the nitrogen (N) content [15]. The contents of potassium (K) and sodium (Na) were measured by flame photometry, and the levels of copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), calcium (Ca), and magnesium (Mg) were determined via atomic absorption spectrophotometry [14] and NaCl [16].

The mineral recovery rate (MRR) was calculated according to [17] based on the difference in the mineral content at the time of sealing and opening using the following equation:

$$\text{MRR } (\%) = (\text{FMo} \times \text{FDMo} \times \text{MCo})/(\text{FMc} \times \text{FDMc} \times \text{MCc}) \times 100 \quad (2)$$

where MRR is the mineral recovery rate% (N, P, Na, K, Cu, Fe, Mn, Zn, Ca, Mg, and Cl); FMo is the forage mass at the time of opening (kg); FDMo is the forage dry matter content at the time of opening (%); MCo is the mineral content (N, P, Na, K, Cu, Fe, Mn, Zn, Ca, Mg, and Cl) at the time of opening (% DM); FMc is the forage mass at the time of closing (kg); FDMc is the forage dry matter content at the time of closing (%); and MCc is the mineral content (N, P, Na, K, Cu, Fe, Mn, Zn, Ca, Mg, and Cl) at the time of closing (% DM).

2.6. Statistical Model and Analysis

For the first experiment in the field, the variables were analysed in a randomised block design according to the following model:

$$\text{Y} = \alpha + \beta + \text{e} \quad (3)$$

where Y is the measured variable; α is the fixed effect of the treatment (irrigation leaching fractions); β is the random effect of the block; and 'e' is the residual error. The PROC REG was used for regression analysis, employing the Software Statistical Analysis System (SAS University) [18], with an analysis of variance and regression at $p = 0.05$. As a criterion for selecting the regression models (linear and quadratic), we adopted the significance of the parameters and coefficients of determination.

For the second experiment, the silages were analysed in a completely randomised design according to the following model:

$$\text{Yij} = \text{P} + \text{Ti} + \text{eij} \quad (4)$$

where Yij is the observed value of the dependent variable; P is the overall mean; Ti is the effect of treatment; and eij is the experimental error. The results obtained were analysed using the PROC-GLM tool of the Software Statistical Analysis System (SAS University) [18], with an analysis of variance and regression at $p = 0.05$. As a criterion for selecting the regression models (linear and quadratic), we adopted the significance of the parameters and coefficients of determination.

3. Results

3.1. Macro- and Micro-Minerals of Sorghum Silage

In silage, the leaching fractions showed a positive linear effect ($p < 0.05$) on N, with a higher mean value observed for the 1% fraction and a maximum for the 15% fraction (Table 3). The leaching fractions had a negative linear effect on the contents of P, K, S, and Na ($p < 0.05$) of the silage, with the lowest levels being obtained for the highest leaching fraction (15%). For both Ca and Mg, a quadratic effect ($p < 0.05$) was observed, with higher values for the 0% and 5% fractions, respectively. Likewise, the composition of micro-nutrients in the silage was modified by the leaching fractions (Table 3). The content of B responded in a decreasingly linear way ($p = 0.037$), and the maximum value was obtained for the 15% fraction (Table 3), whereas Mg exhibited the opposite trend, with an increasing linear effect ($p < 0.05$). There was a quadratic response of the contents of Cu, Fe, Zn, and Cl ($p < 0.05$) of the silage; Cu and Fe were highest in the 10% leaching fraction.

Table 3. Macro- and micro-minerals of IPA 2502 sorghum silage irrigated with different leaching fractions of brackish water.

Minerals	Leach Fractions				SEM	*p*-Value	
	0	5	10	15		L	Q
			Macro-minerals (g kg^{-1})				
Nitrogen [1]	9.17	9.76	10.99	11.59	0.40	0.021	0.994
Phosphorus [2]	2.40	1.79	1.71	1.52	0.30	0.036	0.760
Potassium [3]	9.00	8.00	7.00	5.00	0.52	0.002	0.473
Calcium [4]	8.01	4.86	4.34	6.07	0.51	0.065	0.006
Magnesium [5]	8.29	8.90	7.93	8.20	0.30	0.687	0.050
Sulfur [6]	0.82	0.45	0.29	0.24	0.26	0.025	0.949
Sodium [7]	0.90	0.90	0.85	0.82	0.69	<0.001	<0.001
			Micro-minerals (mg kg^{-1})				
Boron [8]	27.12	19.36	18.11	15.80	0.36	0.037	0.360
Copper [9]	10.49	9.90	11.84	9.96	5.35	0.315	0.042
Iron [10]	144.72	128.07	172.55	130.27	1.85	0.713	<0.001
Manganese [11]	45.99	46.15	47.04	60.37	0.33	<0.001	<0.001
Zinc [12]	20.54	20.88	20.09	19.36	10.31	0.083	0.044
Chloride [13]	16.90	18.00	13.50	19.10	0.78	0.470	0.009

MSE = Mean standard error; L = Linear; Q = Quadratic; Significance at 5% probability. Equations: Macro-minerals—[1] $\hat{y} = 9.104000 + 0.169800x$, $R^2 = 0{,}97$; [2] $\hat{y} = 2.263000 - 0.05400x$, $R^2 = 0.85$; [3] $\hat{y} = 9.200000 - 0.260000x$, $R^2 = 0.96$; [4] $\hat{y} = 7.991000 - 0.858800x + 0.048800x^2$, $R^2 = 0.99$; [5] $\hat{y} = 8.431000 + 0.026200x - 0.003400x^2$, $R^2 = 0.21$; [6] $\hat{y} = 0.735000 - 0.038000x$, $R^2 = 0.87$; [7] $\hat{y} = 911.000000 - 5.800000x$, $R^2 = 0.89$. Micro-minerals—[8] $\hat{y} = 25.379000 - 0.704200x$, $R^2 = 0.85$; [9] $\hat{y} = 10.172500 + 0.200500x - 0.012900x^2$, $R^2 = 0.17$; [10] $\hat{y} = 137.325500 + 3.867100x - 0.256300x^2$, $R^2 = 0.13$; [11] $\hat{y} = 43.283000 + 0.0880600x$, $R^2 = 0.65$; [12] $\hat{y} = 20.599500 + 0.073900x - 0.010700x^2$, $R^2 = 0.94$; [13] $\hat{y} = 17.667500 - 0.631500x - 0.045100x^2$, $R^2 = 0.30$.

3.2. Percentages of the Recovery of Macro- and Micro-Minerals from Silage

As a consequence of the effect of leaching fractions on the mineral composition of sorghum and its silage, there was a change in the dynamics of mineral recovery. The level of N increased linearly, with the maximum recovery rate reaching 10% treatment ($p < 0.05$) ($p < 0.05$) (Table 4). There was also a quadratic effect on the recovery of P, Mg, Zn, Na, and Cl ($p < 0.05$). Both K and Ca showed a decreasingly linear response ($p < 0.05$) to the leaching fraction.

Table 4. Recovery of macro- and micro-minerals (%) in silage of sorghum cultivar IPA 2502 irrigated with different leaching fractions of brackish water.

Minerals	Leach Fractions				SEM	*p*-Value	
	0	5	10	15		L	Q
			Macro-minerals (%)				
Nitrogen [1]	98.23	95.35	106.13	101.36	1.23	<0.001	0.205
Phosphorus [2]	39.30	65.12	59.08	69.93	3.52	<0.001	<0.001
Potassium [3]	67.36	50.96	51.32	32.17	3.76	<0.001	0.072
Calcium [4]	89.82	76.88	75.21	69.30	2.27	<0.001	0.001
Magnesium [5]	95.46	102.33	97.78	85.89	1.83	<0.001	<0.001
Sodium [6]	62.18	61.42	81.02	53.76	3.12	0.019	<0.001
			Micro-minerals (%)				
Manganese [7]	89.80	119.43	105.74	113.81	1.83	<0.001	<0.001
Zinc [8]	58.57	80.51	60.03	62.80	2.67	0.030	<0.001
Chloride [9]	89.82	84.93	54.46	90.08	4.46	<0.001	<0.001

MSE = Mean standard error; L = Linear; Q = Quadratic; Significance at 5% probability. Equations: Macro-minerals—[1] $\hat{y} = 97.284000 + 0.399800x$, $R^2 = 0.31$; [2] $\hat{y} = 41.737500 + 3.9625x - 0.149700x^2$, $R^2 = 0.78$; [3] $\hat{y} = 66.234000 - 2.104200x$, $R^2 = 0.89$; [4] $\hat{y} = 87.287000 - 1.264600x$, $R^2 = 0.89$; [5] $\hat{y} = 95.664000 + 2.148800x - 0.187600x^2$, $R^2 = 0.99$; [6] $\hat{y} = 58.769000 + 3.951800x - 0.275000x^2$, $R^2 = 0.45$. Micro-minerals (%) [7] $\hat{y} = 93.0540000 + 4.400800x - 0.215600x^2$, $R^2 = 0.57$; [8] $\hat{y} = 61.853500 + 2.719700x - 0.191700x^2$, $R^2 = 0.30$; [9] $\hat{y} = 94.403500 - 6.670300x + 0.405100x^2$, $R^2 = 0.51$.

3.3. Macro- and Micro-Minerals in Sorghum

The contents of N, P, Ca, Mg, and S in sorghum were not affected by irrigation depth ($p > 0.05$). The accumulation of Mn showed a quadratic effect ($p < 0.05$), with a higher value also in the fraction of 15%. The Na content showed a quadratic effect ($p < 0.05$), with a higher value in fractions of 5% and 15% (Table 5).

Table 5. Macro-mineral and micro-nutrient composition of sorghum cultivar IPA 2502 irrigated with different leaching fractions of brackish water prior to ensiling.

Minerals	Leach Fractions				SEM	*p*-Value	
	0	5	10	15		L	Q
			Macro-minerals (g kg^{-1})				
Nitrogen	8.38	9.78	9.87	10.30	0.35	0.084	0.486
Phosphor	1.11	1.22	1.12	1.18	0.27	0.976	0.974
Potassium	12.00	15.00	13.00	14.00	0.44	0.215	0.170
Calcium	5.63	6.04	5.50	7.89	0.40	0.069	0.174
Magnesium	7.80	8.31	7.73	8.60	0.30	0.557	0.793
Sulfur	0.84	0.80	0.86	0.82	0.20	0.383	0.502
Sodium [1]	1.30	1.40	1.00	1.40	49.42	<0.001	<0.001
			Micro-minerals (mg kg^{-1})				
Copper	4.36	4.59	4.23	4.76	0.31	0.553	0.356
Iron [2]	90.16	89.27	95.68	106.97	2.14	<0.001	<0.001
Manganese [3]	46.00	36.92	42.40	47.78	1.28	0.007	<0.001
Zinc	31.50	24.78	31.90	27.70	0.92	0.208	0.087
Chloride [4]	16.87	20.25	23.62	19.125	0.78	0.009	<0.001

MSE = Mean standard error; L = Linear; Q = Quadratic; Significance at 5% probability. Equations: Macro-minerals—[1] $\hat{y} = 1365.00000 - 47.000000x + 3.000000x^2$, $R^2 = 0.21$; Micro-minerals—[2] $\hat{y} = 86.994000 + 1.136800x$, $R^2 = 0.81$; [3] $\hat{y} = 45.267000 - 1.952600x + 0.144600x^2$; $R^2 = 0.84$; [4] $\hat{y} = 16.481250 + 1.383750x - 0.078750x^2$, $R^2 = 0.86$.

The Fe content ($p < 0.05$) was positively linearly affected by the leaching fraction, with a higher mean value observed for the 15% fraction. There was an effect on the Cl^- content ($p < 0.05$), with a higher mean value observed for the 10% leaching fraction. We observed no effects of the leaching fractions on Cu and Zn ($p > 0.05$).

4. Discussion

Leaching fractions did not alter the uptake and accumulation of the macro-minerals P, K, N, Mg, and Ca. In contrast, for Na, even with an increase of 100 g kg^{-1} Na^+ in the 5% and 15% leaching fractions, there was no impact on the plants. Based on a previous study, Na is one of the minerals that regulate osmolarity and can be accumulated in plant tissue, causing an imbalance in cells [19]. Normally, increasing leaching depths decrease Na^+ uptake and accumulation, which improves the photosynthetic capacity of the plant because of the reduction in Na^+ toxicity and increased K^+:Na^+ and Ca^{2+}:Na^+ ratios [1,20,21].

The leaching fraction at 15% promoted the accumulation of Fe, an essential element in the structural and metabolic development of the plant. However, its solubility and availability are influenced by stable oxides, hydroxides, and oxy-hydroxides [22,23], demonstrating that leaching fractions up to 15% do not interfere with Fe solubility. The Fe homeostasis is tightly controlled due to its participation in the reduction in ribonucleotides and molecular nitrogen [24] as well as the transfer of electrons that produce energy via respiration and photosynthesis [25]. The Fe content found in this study is within the appropriate range for grasses, which is 82.4–182.4 mg kg^{-1} [26]. Another micro-nutrient affected by the leaching fractions was Mn, which was reduced by 1.95 mg kg^{-1} for each unit (1%) of the applied fraction. The inhibitory effect on the accumulation of Mg is related to the saturation of water in the soil, which implies the reduction in Mn (III) and Mn (IV) [27]; Mn contents between 37.4 and 60.3 mg kg^{-1} are appropriate for grasses [26].

In silage, the N content responded in an increasingly linear way to increasing leaching fractions. The increase in nitrogen compounds in the silage fermentation profile and the development of microorganisms incorporate nitrogen in the silage. The decrease in *Kosakonia* and the increase in *Clostridium* caused the higher contents of non-protein N and free amino acids in the silages [28]. This effect also explains the reduction in P due to anabolism and catabolism, requiring inorganic P for ATP generation. Moreover, acidification by homolytic bacteria requires glucose or fructose + 2 ADP + inorganic P to generate 2 lactate + 2ATP + 2 H_2O, reducing the P content [29].

Silage fermentation reduced the contents of K, S, and Na with an increase in the leaching fraction. The decrease in Na and K is linked to osmolarity and water activity inside the silo. Because water has a bipolar shape, it is electrically attracted by cations and ions, which favors the loss of these minerals by the leaching process in the production of effluents. The contents of K and S are similar to those reported elsewhere [30], with values of 1.02 to 16.83 g k^{-1} (K) and 0.07 to 1.24 g kg^{-1} (S) for corn silages. The Na content, on the other hand, was higher than that found in a previous study [29], with values ranging from 0.23 to 3.56 g kg^{-1}. The contents of Ca and Mg demonstrate an alteration in the selectivity of the cell membrane, in addition to the reduction in Mg, which is related to its water-soluble fraction [31], promoting a greater loss of this mineral during the fermentation process.

In relation to the silage micro-minerals, Fe and Zn showed a quadratic response, which may be related to the increased phytate concentration in the silage, inhibiting Fe and Zn [32]. Phytic acid represents 70% of the phosphates in seeds, integrated into minerals or proteins in complex forms [33]. In addition, the soluble fibre in the seed contains 75% phytic acid [34]. The increased Mn content in the silage may be a result of the increase in the number of lactic bacteria as they can accumulate large amounts of Mn [29]; moreover, the microorganisms in the rhizosphere can help plants to adapt to abiotic stress [35]. According to a previous report [36], report plants tolerant to salt stress have low rates of Na^+ and Cl^- transport, which was also observed in this study since the levels of these elements in the 15% leaching fraction approached those of the control treatment. The Cu content in silages was within the appropriate range for forage sorghum, from 5 to 20 mg kg^{-1} [37].

The increase in N recovery as the leaching fraction increased may be associated with the activity of the microorganisms since they present a source of N in their cell structure, such as the strains of *Azospirillum*, which are adapted to salt stress [38]. In turn, the recovery of P and K depends on the fermentation process. The ammonia released by hydrolysis reduces losses during the fermentation process [39], whereas in mixed silages (i.e., sorghum + *U. brizantha*), lower losses of P and K have been observed [40].

The leaching fractions altered the Na recovery ($p < 0.05$) with a reduction in the fraction of 15%, which is due to the high solubility of tNa [41]. The high uptake of Na^+ in an environment under salt stress [42] affects the assimilation of K^+; therefore, in the present study, the Na^+ content also affected the K^+ recovery because of the synergism between these elements. The opposite was observed for Cl^-, which showed greater recovery when the levels of Na^+ recovery were reduced (15% leaching fraction) and decreased with an increase in Na^+ recovery (10% leaching fraction). In saline soils, an increase in the concentration of Na and a reduction in exchangeable Ca promotes ionic imbalance [43]. In the case of Mg, the high recovery is due to the activity of lactic acid bacteria that accumulate Mn [29,44]. For micro-nutrients, Zn recovery was related to the plug process, which is the accumulation of buffers containing Zn, hindering the rise of crude sap [37]; therefore, the movement of minerals to the bottom of the silo may have increased.

5. Conclusions

The use of brakish water leaching fractions up to 15% in sorghum irrigation allows the removal of salts, such as Na, from the root zone. The increase in the amount of brackish water in sorghum irrigation allowed the production of silages with lower concentrations of Ca, P, K, and Na and lower proportions of B, Cu, Fe, and Zn. Therefore, the recovery of minerals is mainly affected by the losses of K, Ca, Mg, and Na.

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