

Article

Pearl Millet Genotypes Irrigated with Brackish Water Under Different Levels of Agricultural Gypsum

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Abstract: The aim was to evaluate the productivity, agronomic characteristics, and chemical and mineral composition of pearl millet genotypes irrigated with brackish water under the application of agricultural gypsum in two cuts. The experiment was a randomized block design in a 4 (gypsum levels—0, 2, 4, and 8 ton ha^{−1} applied on the surface) × 3 (pearl millet genotypes—ADR 300, BRS 1501, and IPA BULK 1BF) factorial arrangement, with three replications, irrigated with high brackish water and low sodium. Agricultural gypsum had no significant effect on productivity, agronomic characteristics, and chemical and mineral composition ($p > 0.05$). In the first cut, higher mean values were found for the percentage of panicle, crude protein, ether extract, in vitro dry matter digestibility, calcium, sulfur, and manganese ($p < 0.05$). For the second cut, higher results were observed for green matter productivity, dry matter productivity, water use efficiency, stem percentage, stem diameter, average leaf size, panicle size, acid detergent fiber, lignin, cellulose, total carbohydrates, potassium, and copper ($p < 0.05$). IPA Bulk 1 BF showed a larger panicle size in both cuts ($p < 0.05$). The evaluated pearl millet genotypes showed desirable agronomic characteristics and tolerance to irrigation with brackish water regardless of gypsum application, thus they are indicated for cultivation in the semi-arid regions.

Keywords: biosaline agriculture; gypsum application; *Pennisetum glaucum* (L.) R. Br.; semiarid



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1. Introduction

In the Brazilian Northeast, mainly arid and semi-arid regions, the high content of salts in the soil has several effects on the plants, including osmotic disorders that inhibit water uptake by the roots and promote nutritional imbalance and ion toxicity [1,2]. Despite the high content of soluble salts in water resources available in arid regions, in the absence of other sources, brackish water is the only option to be used by producers both for irrigation and for animal consumption [3].

There is a constant search for viable alternatives to ameliorate soil salinity and minimize its impacts on the environment. Among the available management techniques, the use of agricultural gypsum is a viable alternative to neutralize aluminum toxicity in the subsurface layer of the soil [4,5]. The solubility of agricultural gypsum and the presence of water in the soil interfere with its movement along the profile. This movement of gypsum contributes to reducing aluminum toxicity in the subsoil and increasing the availability of sulfur and percolation of bases, enabling the improvement of the root system in the deepest layers of the soil [6,7].

Pearl millet (*Pennisetum glaucum* (L.) R. Brown) is considered an excellent alternative for grain and forage production in arid or semi-arid regions due to its adaptation to drought and sandy soils with low organic matter, and low fertility [8]. Being hardy and robust in nature, pearl millet could survive under multiple abiotic stresses particularly drought, heat, and alkalinity/salinity [9] (Toderich et al., 2018). These properties demonstrate its promising potential as a forage plant that can be used strategically in animal feed in semi-arid conditions, with satisfactory productivity and development [10,11] when irrigated with brackish water [12–14] and using gypsum application techniques [15,16].

Adaptation strategies that focus on varietal selection are often considered a cost-effective and practical solution for reducing productivity gaps and optimizing agricultural performance in regions prone to environmental stress. The differences observed among the evaluated pearl millet genotypes may be attributed to the inhibitory effects of excessive ion accumulation and hyperosmotic stress, which can compromise root water conductivity and increase leaf tissue water loss [17] (Sheoran et al., 2021).

Studies are required to understand the use of irrigation with brackish water as well as the benefits of agricultural gypsum in forage production as a strategy for ranchers. It is known that pearl millet is a salt-stress-tolerant species [18–20], but it has been hypothesized that progressive application of increasing doses of agricultural gypsum in soils without salinity would neutralize the deleterious effects resulting from irrigation with brackish water. Thus, the present study aimed to evaluate the productivity, agronomic characteristics, and chemical and mineral composition of pearl millet genotypes irrigated with brackish water under agricultural gypsum application in two cuts.

2. Materials and Methods

2.1. Experiment Location

The experiment was conducted in the Biosaline Agriculture Studies area in the Caatinga Experimental Field, belonging to Embrapa Semiárido, in Petrolina, State of Pernambuco, in the São Francisco sub-medium region (latitude 9°8'8.9" S, longitude 40°18'33.6" W, 373 m altitude) between September 2017 and January 2018. The climate of the region is classified, according to Köppen, as semi-arid BSh. Rainfall is concentrated between November and April, with an average annual rainfall of around 400 mm, irregularly distributed. During the experimental period, the average relative air humidity was 54.42%, the average temperature was 27.45 °C, with an average evapotranspiration of 5.32 mm and an average rainfall of 0.57 mm [21].

2.2. Treatments and Experimental Design

The treatments consisted of three cultivars of pearl millet (ADR 300, BRS 1501, and IPA BULK 1BF) and four levels of agricultural gypsum (0, 2, 4, and 8 ton ha⁻¹), applied on the surface. The experiment was a randomized block design in a 4 × 3 factorial arrangement, with three replications, totaling 36 plots.

2.3. Characterization of the Experimental Area and Irrigation

The soil of the experimental area is classified as Red Yellow Argisol [22], with medium texture. Soil samples were collected to analyze their chemical properties, at the beginning and end of the experiment (Table 1).

Table 1. Chemical and physical composition of the initial and final soil of the experimental area.

		Initial		Final	
		Layer (cm)		Layer (cm)	
		0–20	20–40	0–20	20–40
EC	mS cm ^{−1}	1.33	2.20	3.48	2.79
pH	-	4.60	5.70	4.34	4.37
Total Carbon	g kg ^{−1}	4.60	4.10	-	-
K ⁺	cmol dm ^{−3}	0.23	0.16	0.64	0.39
Na ²⁺	cmol dm ^{−3}	0.27	0.68	0.34	0.31
Ca ²⁺	cmol dm ^{−3}	1.60	1.40	2.73	3.04
Mg ²⁺	cmol dm ^{−3}	0.60	0.60	1.17	1.32
Al ³⁺	cmol dm ^{−3}	0.05	0.00	0.04	0.13
CEC	cmol dm ^{−3}	4.2	5.6	5.95	6.61
SB	cmol dm ^{−3}	2.7	2.8	4.88	5.08
H + Al	cmol dm ^{−3}	1.5	2.7	1.06	1.53
P	mg dm ^{−3}	6.14	1.44	5.20	5.81
Cu	mg dm ^{−3}	1.07	1.65	1.15	1.36
Fe	mg dm ^{−3}	21.4	23.0	8.91	10.31
Mn	mg dm ^{−3}	18.2	14.6	6.19	4.53
Zn	mg dm ^{−3}	4.54	3.13	0.72	0.45
V	%	64.00	50.90	77.35	76.57
Soil	kg dm ^{−3}	1.49	1.37	1.31	1.27
Particles	kg dm ^{−3}	2.59	2.51	2.57	2.54
Porosity	%	42.40	45.41	20.51	34.54
Sand	g kg ^{−1}	808.1	721.7	735.05	587.90
Silt	g kg ^{−1}	116.9	196.3	143.36	159.42
Clay	g kg ^{−1}	75.0	83.0	121.61	252.68

EC = electrical conductivity of the saturation extract; pH determined in water at a ratio of 1:2.5; K⁺ = exchangeable potassium; Na²⁺ = exchangeable sodium; Ca²⁺ = exchangeable calcium; Mg²⁺ = exchangeable magnesium; Al³⁺ = exchangeable aluminum; CEC = cation exchange capacity at pH 7.0; SB = Sum of bases; H + Al = Potential acidity; P = available phosphorus extracted by Mehlich; Cu = available Copper; Fe = available Iron; Mn = available Manganese; Zn = available Zinc; V = base saturation.

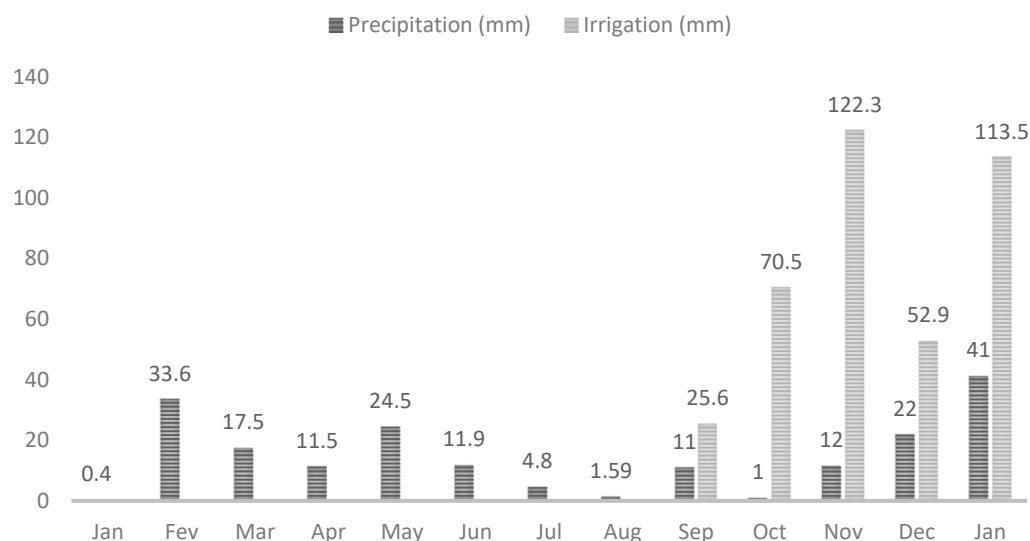
Irrigation was performed three times a week with brackish water from an underground well. Water was applied according to the evapotranspiration of the crop (ET_c), obtained through the evapotranspiration measured in the period (ET_o) and the cultivation coefficient (K_c) of the crop (1.00–1.10). The drip tube irrigation was superficial with emitters and a nominal flow of 1.6 L h^{−1}, a nominal diameter of 16 mm, and spaced 0.20 m apart. Samples of the water used for irrigation were collected weekly during the experimental period to analyze their chemical characteristics (Table 2). Water was identified as C3S1, indicating high salinity, low sodium content, and an average hardness of 109.76 mg L^{−1}, which is considered as moderate. Total dissolved solids were equal to 1107 mg L^{−1}, and residual sodium carbonate (RSC) was equal to 3.38 meq L^{−1}, indicating the presence of excess bicarbonate/carbonate relative to calcium and magnesium ions [23].

The agrometeorological data necessary for the determination of ET_o were obtained from the National Institute of Meteorology [24] and the ET_c was determined by the soil water balance. Figure 1 illustrates the water distribution in the experimental period.

Table 2. Chemical composition of water used for irrigation.

Chemical Composition									
pH	EC	Ca ²⁺	Na ⁺	Mg ²⁺	K ⁺	Cl [−]	TH	SAR	RSC
	ds.m ^{−1}	mmol.L ^{−1}					mg.L ^{−1}		meq.L ^{−1}
7.38	1.73	15.14	3.72	6.89	0.29	22.4	109.76	0.62	3.38

pH = Hydrogenionic potential; EC = Electrical conductivity; Ca²⁺ = Exchangeable calcium; Na⁺ = Exchangeable sodium; Mg²⁺ = Exchangeable magnesium; K⁺ = Exchangeable potassium; Cl[−] = Chlorides; TH = Total Hardness; SAR = Sodium adsorption ratio.

**Figure 1.** Water distribution in the experimental period.

2.4. Planting and Crop Treatments

The spacing used in the crop was 0.60 m between rows. The plots were 6 m long and 3.6 m wide. Pearl millet sowing was carried out in furrows, at a depth of approximately 1.0 cm. At 15 days before sowing, based on soil analysis, 50 ton ha^{−1} organic matter and gypsum were manually applied, according to treatments. The applied gypsum doses were calculated based on the initial soil analysis and adopting regular increasing values, using the formula: $CEC \times (70\% - SB/CEC) \times 100/250 = 0.27 \text{ ton ha}^{-1}$, where 70% is the desired base saturation, 100 kg ha^{−1} is the factor equivalent to 1 cmolc dm^{−3}, and 250 kg of Ca per ton represents 25% of Ca. The first dose was considered 0 and the others were 2, 4, and 8 ton ha^{−1}.

Nitrogen fertilization was applied with 50 kg ha^{−1} N, as urea: the first at sowing, with 20 kg ha^{−1} N, surface broadcast, and the second at 20 days after planting (DAP), with 30 kg ha^{−1} N via fertigation. Fertilization was also carried out with 60 kg ha^{−1}, as single superphosphate, and with 20 kg ha^{−1} K, as potassium chloride.

The organic matter used consisted of bovine and goat manure, with the following characteristics: electrical conductivity = 12.27 mS cm^{−1}; pH = 8.3; phosphorus = 355.39 mg dm^{−3}; potassium = 243.5 cmol dm^{−3}; sodium = 20.3 cmol dm^{−3}; calcium = 6.4 cmol dm^{−3}; and magnesium = 2.5 cmol dm^{−3}; copper = 1.45 mg dm^{−3}; iron = 5.36 mg dm^{−3}; manganese = 58.13 mg dm^{−3}, and zinc = 2.43 mg dm^{−3}.

In this study, the gypsum used presented a purity of approximately 90%, with a chemical composition of 29% calcium oxide (CaO) and 16% sulfur (S). The particle size distribution was predominantly fine particles (<0.2 mm mesh) and the solubility of the gypsum was approximately 2.4 g/L at 25 °C.

At 15 DAP, thinning was performed to obtain 15 plants linear m^{-1} . At 30 DAP, a manual weeding was carried out, followed by a preventive application of insecticide against fall armyworm (*Spodoptera frugiperda*) 60 days after planting.

2.5. Morpho-Agronomic Characterization

The morpho-agronomic characteristics were evaluated in four plants per plot, on the central row. The measured variables were plant height (PH, in meters), stem base diameter (SD, in centimeters), average leaf size (ALS, in centimeters), panicle size (PS, centimeters), number of leaves (NL), and number of tillers (NT), measured with measuring tape and a digital caliper. For agronomic characterization, four plants were randomly selected per plot and separated into the constituents: leaf blade, stem, and panicle. The material was weighed and dried in a forced ventilation oven at 55 °C for 72 h, until reaching a constant weight, to establish the proportion based on dry matter.

2.6. Pearl Millet Harvest

The first cut of the pearl millet was made 75 DAP. The regrowth plants were harvested 65 days after the first cut. The cuts were made manually, with a cleaver, 10 cm above the ground, obtaining as reference the two central rows of each plot. In both cuts, pearl millet was harvested when the grains were at the milky/dough stage.

The harvested material was ground in a forage machine (PP35, Pinheiro Máquinas Agrícolas, Itapira, SP, Brazil) regulated to cut the particles to an average size of 2 cm. The ground material was homogenized and sampled for further laboratory analysis.

2.7. Laboratory Analysis

2.7.1. Chemical Composition

Samples of the fresh material were pre-dried in a forced ventilation oven at 55 °C for 72 h and processed in a knife mill (Wiley mill, Marconi, MA–580, Piracicaba, Brazil) using 1 mm sieves. Laboratory analyses were performed using the methods described by AOAC [25] for dry matter (DM; method 967.03), mineral matter (MM, method 942.05), crude protein (CP; method 981.10), and ether extract (EE; method 920.29).

The content of neutral detergent fiber (NDF) and acid detergent fiber (ADF) was determined as described by Van Soest et al. [26]. Lignin (LIG) was determined by treating the fiber residue in acid detergent with 72% sulfuric acid [27]. Hemicellulose (HEM) and cellulose (CEL) were calculated using the following equations:

$$HEM = NDF - ADF$$

$$CEL = ADF - LIG$$

Total carbohydrates (TC) were calculated using the following equation [28]:

$$TC (\%) = 100 - (\% CP + \% EE + \% MM)$$

The analysis of in vitro dry matter digestibility (IVDMD) was performed according to Tilley and Terry [29], with modification proposed by Holden [30].

2.7.2. Mineral Analysis

The concentrations of potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), and sodium (Na) were determined according to methodologies described by Nogueira and Souza [31]. The levels of Na and K were determined by flame photometry and the Ca and Mg concentrations were analyzed by titration. This involved determining the Ca content and, subsequently, the Ca + Mg content, with the Mg concentration being defined as the difference. The S levels were

determined indirectly, first by obtaining the sulfate concentrations and, later, by considering the atomic molecular weight, the S concentration was determined. The Cu, Fe, Mn, and Zn were determined using an atomic absorption spectrophotometer (model Analyst 100, PerkinElmer®, River Valley, Singapore).

2.8. Green Matter Productivity, Dry Matter Productivity, and Water Use Efficiency

The green matter productivity (GMP) per hectare was obtained by multiplying the product between the production per linear meter cultivated and the total of linear meters cultivated per hectare. The dry matter productivity (DMP) was estimated by multiplying the green matter production and the dry matter content and subsequently converting the result into dry matter production per hectare [32]. The water use efficiency (WUE) of the two cycles was estimated by dividing the DMP by the amount of water accumulated during the cycle [33].

2.9. Statistical Analysis

Data were subjected to Shapiro–Wilk and Levene tests to check the normality of the residues and homogeneity of the variances, respectively. Once the assumptions were met, they were tested by analysis of variance (ANOVA). The analysis of variance was performed using the Proc MIXED of SAS (Statistical Analysis System—version 9.3). The covariance matrix was chosen using the Bayesian information criterion [34] to determine the model that best represented the data. The interactions were broken down when significant. When appropriate, means were calculated using “LSMEANS” and comparisons were made using “PDIFF”. Significant differences were declared when $p \leq 0.05$. When a significant effect was detected for the gypsum dose, the relationships were quantified using polynomial regression and assessed for quality of fit (R^2) and significance.

3. Results

There were no significant interactions ($p > 0.05$) between the tested pearl millet genotypes, cuts made, and levels of gypsum applied for the variables GMP, DMP, DM, and WUE (Table 3). There was a difference for GMP, DMP, and WUE between the cuts made in the tested pearl millet genotypes ($p < 0.05$), with higher values observed for the second cut (regrowth) (Table 3). The applied gypsum levels did not cause a significant effect between the cuts made in the pearl millet ($p > 0.05$) for the studied variables (Table 3).

Table 3. Green matter productivity (GMP), dry matter productivity (DMP), dry matter content (DM), and water use efficiency (WUE) of pearl millet genotypes in the respective cuts and applications of gypsum doses.

Varieties	GMP (kg ha ⁻¹)		DMP (kg ha ⁻¹)		DM (%)		WUE (kg DM ha ⁻¹ mm ⁻¹)	
	Cuts							
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
ADR 300	21,820.50 b	46,819.43 a	5775.88 b	12,070.05 a	26.47	25.58	66.19 b	151.48 a
BRS 1501	27,594.00 b	48,430.55 a	6931.61 b	11,812.21 a	25.12	24.39	85.24 b	159.63 a
IPA Bulk 1BF	26,640.00 b	40,513.89 a	6854.47 b	10,136.57 a	25.73	25.02	81.62 b	132.42 a
Gypsum doses applied								
0 (ton ha ⁻¹)	24,486.00	42,703.68	5920.71	10,043.90	24.18	23.52	76.59	142.37
2 (ton ha ⁻¹)	25,920.00	48,666.66	6892.13	12,629.00	26.59	25.95	78.50	157.10
4 (ton ha ⁻¹)	25,176.00	47,685.18	6545.76	11,969.00	26.00	25.10	76.86	155.69
8 (ton ha ⁻¹)	25,824.00	41,962.95	6802.04	10,784.47	26.34	25.70	76.86	135.91
VC %	28.45	15.82	8.78	9.23	8.89	9.47	18.42	13.57

VC—variation coefficient; Different lowercase letters differ by cutting through the Tukey test at 5% probability.

The stem percentage of pearl millet genotypes was higher in the second cut ($p < 0.05$). The panicle showed a higher proportion in the first cut ($p < 0.05$), with a higher percentage of panicles for the Bulk 1 BF pearl millet ($p < 0.05$) in the two cuts made (Table 4). There was no significant effect of cut or genotype on the percentage of leaf ($p > 0.05$). Gypsum levels had no significant effect on the cuts and genotypes of pearl millet evaluated ($p > 0.05$) (Table 4).

Table 4. Percentage of the leaf blade, stem, and panicle of pearl millet genotypes in the respective cuts and applications of gypsum doses.

Varieties	Leaf Blade (%)		Stem (%)		Panicle (%)	
	Cuts					
	1st	2nd	1st	2nd	1st	2nd
ADR 300	22.30	16.88	59.64 b	70.97 a	19.02 aB	12.34 bB
BRS 1501	20.26	15.33	60.30 b	71.75 a	19.03 aB	12.20 bB
IPA Bulk 1 BF	20.60	16.04	56.10 b	67.19 a	23.25 aA	15.74 bA
Gypsum doses applied						
0 (ton ha ⁻¹)	20.80	15.80	59.23	70.17	19.23	13.37
2 (ton ha ⁻¹)	21.80	16.35	59.47	70.53	20.64	12.48
4 (ton ha ⁻¹)	19.84	16.51	55.84	70.28	23.85	13.10
8 (ton ha ⁻¹)	21.85	15.62	57.27	68.70	20.95	14.91
VC %	25.41	27.12	23.20	27.75	27.22	29.96

VC—variation coefficient; Different lowercase letters differ from each other by cutting using the Tukey test at 5% probability; Different capital letters differ among cultivars by the Tukey test at 5% probability.

The stem diameter, average leaf size, and panicle size were higher in the second cut of pearl millet genotypes ($p < 0.05$). The Bulk 1 BF genotype showed the largest panicle sizes compared to the other tested pearl millet genotypes ($p < 0.05$) (Table 5). There was no effect of cut or genotype on plant height, number of leaves, or number of petioles ($p > 0.05$). Gypsum levels did not promote a significant effect between the cuts and genotypes of pearl millet evaluated ($p > 0.05$) (Table 5).

Table 5. Morpho-agronomic characteristics of pearl millet genotypes in the respective cuts and applications of gypsum doses.

Varieties	PH (m)		SD (cm)		ALS (cm)		PS (cm)		NL (n°)		NT (n°)	
	Cuts											
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
ADR 300	1.47	1.55	1.03 b	1.30 a	41.70 b	49.07 a	22.39 bB	23.95 aB	8.45	8.12	1.91	2.66
BRS 1501	1.46	1.62	1.04 b	1.31 a	42.42 b	52.09 a	21.69 bB	24.37 aB	8.70	7.75	2.25	2.37
IPA Bulk 1BF	1.47	1.60	1.03 b	1.25 a	44.92 b	51.89 a	25.08 bA	27.20 aA	7.54	8.25	2.16	2.87
Gypsum doses applied												
0 (ton ha ⁻¹)	1.51	1.57	1.06	1.32	43.40	50.79	23.19	24.69	8.83	8.05	2.61	2.66
2 (ton ha ⁻¹)	1.48	1.58	1.03	1.23	44.00	51.19	24.09	24.73	8.11	7.83	1.50	2.44
4 (ton ha ⁻¹)	1.44	1.62	1.05	1.27	43.22	51.59	24.08	24.83	7.88	8.22	2.50	2.33
8 (ton ha ⁻¹)	1.43	1.58	1.00	1.32	41.43	50.39	22.18	27.72	8.11	8.05	1.83	3.11
VC (%)	6.68	7.82	9.33	14.91	7.72	9.59	9.24	15.44	18.57	10.51	46.87	28.06

PH—plant height; SD—stem base diameter; ALS—average leaf size; PS—panicle size; NL—number of leaves; NT—number of tillers; VC—variation coefficient; Different lowercase letters differ from each other by cutting using the Tukey test at 5% probability; Different capital letters differ among cultivars by the Tukey test at 5% probability.

The cuts made had a significant effect on the chemical composition of pearl millet genotypes ($p < 0.05$). In the first cut, there were higher contents of CP, EE, and IVDMD. In the second cut, there were higher contents of ADF, lignin, cellulose, and TC (Table 6).

The contents of mineral matter, *NDF*, and hemicellulose did not differ ($p > 0.05$) between genotypes, gypsum levels, and cuts evaluated (Table 6).

Table 6. Chemical composition (in % dry matter) of pearl millet genotypes in the respective cuts and applications of gypsum doses.

Varieties	Crude Protein		Ether Extract		Mineral Matter		Neutral Detergent Fiber		Acid Detergent Fiber	
	Cuts									
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
ADR 300	15.97 a	10.16 b	1.73 a	1.40 b	8.30	8.80	57.63	60.64	26.7 b	33.16 a
BRS 1501	15.75 a	10.56 b	1.71 a	1.44 b	8.49	8.70	58.22	61.17	28.03 b	33.12 a
IPA Bulk 1BF	15.99 a	10.54 b	1.65 a	1.41 b	8.77	9.26	57.31	62.57	26.64 b	33.54 a
Gypsum doses applied										
0 (ton ha ⁻¹)	15.13	10.46	1.62	1.43	8.65	9.10	57.16	60.61	26.88	33.05
2 (ton ha ⁻¹)	16.28	10.33	1.79	1.45	8.67	9.13	57.55	60.90	27.41	33.31
4 (ton ha ⁻¹)	16.64	10.17	1.71	1.44	8.21	8.63	58.21	62.37	26.83	33.76
8 (ton ha ⁻¹)	15.54	10.72	1.67	1.42	8.54	8.82	57.97	61.97	27.44	33.00
VC (%)	6.33	8.68	14.40	23.74	14.90	10.55	4.22	4.09	6.68	4.44
Varieties	Lignin		Cellulose		Hemicellulose		Total carbohydrates		IVDMD	
	Cuts									
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
ADR 300	3.04 b	3.83 a	23.71 b	29.30 a	30.88	27.48	74.00 b	79.64 a	85.63 a	80.84 b
BRS 1501	2.90 b	4.02 a	25.13 b	29.10 a	30.19	28.05	74.05 b	79.30 a	84.67 a	80.06 b
IPA Bulk 1BF	2.92 b	3.78 a	23.72 b	29.76 a	30.67	29.03	73.59 b	78.59 a	85.47 a	80.57 b
Gypsum doses applied										
0 (ton ha ⁻¹)	2.62	3.74	24.26	29.30	30.28	27.56	74.60	79.00	85.23	81.12
2 (ton ha ⁻¹)	3.04	3.91	24.37	29.40	30.14	27.59	73.26	79.09	85.43	81.41
4 (ton ha ⁻¹)	3.01	3.95	23.82	29.81	31.38	28.61	73.44	79.76	85.32	79.00
8 (ton ha ⁻¹)	3.15	3.91	24.29	29.07	30.53	29.00	74.25	78.84	85.05	80.44
VC (%)	15.79	9.50	9.70	3.50	4.89	9.4	9.00	4.50	2.00	2.51

IVDMD—in vitro dry matter digestibility; VC—variation coefficient; Different lowercase letters differ from each other by cutting using the Tukey test at 5% probability.

Calcium and sulfur had their highest concentrations in the first cut, whereas potassium showed a higher concentration in the regrowth of pearl millet ($p < 0.05$) (Table 7). The magnesium contents did not differ ($p > 0.05$) between genotypes, gypsum levels, and cuts evaluated (Table 7).

Table 7. Accumulated macrominerals of pearl millet genotypes in the respective cuts and applications of gypsum doses.

Varieties	Potassium		Calcium		Magnesium		Sulfur	
	Cuts							
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
ADR 300	8.31 b	17.61 a	8.37 a	2.37 b	1.45	2.40	2.72 a	0.84 b
BRS 1501	8.52 b	17.75 a	8.93 a	2.23 b	1.50	2.36	2.60 a	1.58 b
IPA Bulk 1BF	9.83 b	17.85 a	8.95 a	2.46 b	2.09	2.55	2.69 a	1.53 b
Gypsum doses applied								
0 (ton ha ^{−1})	8.61	17.65	8.68	2.52	1.43	2.48	2.57	1.43
2 (ton ha ^{−1})	9.02	18.91	9.52	2.43	1.48	2.45	2.74	1.16
4 (ton ha ^{−1})	8.23	16.86	9.05	2.10	1.54	2.30	2.45	1.19
8 (ton ha ^{−1})	9.70	17.52	7.74	2.37	2.27	2.52	2.92	1.47
VC (%)	22.50	20.46	17.58	16.39	24.85	14.26	20.50	32.14

VC—variation coefficient; Different lowercase letters differ from each other by cutting using the Tukey test at 5% probability.

Regarding microminerals, higher concentrations of copper were found in the second cut made in pearl millet genotypes ($p < 0.05$). The manganese contents were higher in the

first cut ($p < 0.05$) (Table 8). The concentrations of iron, zinc, and sodium did not differ ($p > 0.05$) between genotypes, gypsum levels, and cuts evaluated (Table 8).

Table 8. Accumulated microminerals of pearl millet genotypes in the respective cuts and applications of gypsum doses.

Varieties	Copper		Iron		Manganese		Zinc		Sodium	
					Cuts					
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
ADR 300	15.40 b	89.55 a	223.13	151.81	158.68 a	106.12 b	110.40	90.92	280.00	236.16
BRS 1501	15.31 b	85.40 a	208.25	138.60	161.39 a	117.43 b	110.00	93.53	308.08	270.66
IPA Bulk 1BF	18.46 b	84.89 a	295.91	127.12	175.35 a	102.68 b	115.10	94.00	286.50	255.08
Gypsum doses applied										
0 (ton ha ^{−1})	16.07	88.80	361.05	138.81	152.01	111.03	109.94	93.45	252.44	255.44
2 (ton ha ^{−1})	16.62	80.86	186.46	139.51	178.25	109.11	117.47	92.60	274.66	272.66
4 (ton ha ^{−1})	16.44	90.26	174.22	144.07	168.98	93.84	109.16	89.17	308.33	262.55
8 (ton ha ^{−1})	16.44	86.54	248.00	134.33	161.31	121.00	110.74	96.05	330.66	261.22
VC (%)	10.57	11.16	35.76	25.53	23.75	21.41	10.56	16.13	21.65	12.18

VC—variation coefficient; Different lowercase letters differ from each other by cutting using the Tukey test at 5% probability.

4. Discussion

The increase observed in the variables GMP, DMP, leaf size, and panicle size in the second cut may be associated with the lower amount of brackish water used in the second cut (166.4 mm) when compared to the first cut (218.5 mm), due to rainfall volume. Rainfall in the second cut period was 63 mm, while in the first cut, it was 24 mm. According to Isayenkov and Maathuis [35], the development of plants, in the presence of low to moderate salinity, is significantly reduced due to the negative growth modulation. In these conditions, in general, plants are able to complete their development cycles, but with less productivity [36].

A higher panicle percentage in both cuts suggests that Bulk 1 BF maintains its reproductive investment under stress conditions, which is a key indicator of tolerance. The ability to develop larger panicles indicates that Bulk 1 BF efficiently utilizes resources despite salt stress, ensuring grain production. Greater overall structural growth (stem diameter, leaf size, and panicle size) in the second cut suggests that Bulk 1 BF adapts well over time, demonstrating better regrowth potential under stress. In contrast, ADR 300 and BRS 1501, which had a lower panicle percentage compared to Bulk 1 BF, invested less in reproductive structures, possibly indicating greater sensitivity to stress.

The results obtained for green matter productivity were superior to those found by Buso et al. [37], who obtained GMP of 19,778.47 and 15,637.50 kg ha^{−1} for the ADR 500 genotype, 20,273.26 and 13,459.03 kg ha^{−1} for the BRS 1501 genotype, and 21,813.19 and 11,422.92 kg ha^{−1} for the ADR 7010 genotype in cuts one and two, respectively. Pinho et al. [26] evaluated pearl millet genotypes for silage in the semi-arid region and observed that, with a rainfall index of 230 mm for the first cycle and 355 mm for the second cycle, the GMP for the ADR 500 cultivar was 9500 kg ha^{−1} in the first cut and 10,770 kg ha^{−1} in the second cut. For the BRS 1501 cultivar, which was also used in the present study, the GMP was 11,940 kg ha^{−1} in the first cut and 11,210 kg ha^{−1} in the second cut, values lower than those obtained in the present study.

The higher water use efficiency observed in the second cut of the pearl millet genotypes could have occurred due to the greater rainfall (63 mm) and less salt water (166.4 mm) in the second cut, compared to the first cut, which may have caused stress on the plants and interfered with their development. Ismail [38] evaluated different irrigation methods, in pearl millet, with and without water stress, and proved that the water use efficiency was reduced by water stress and the number of cuts.

Santos et al. [8] and Singh et al. [39] evidenced that the increase in the accumulation of phytomass in pearl millet is observed predominantly in the proportion of stem, followed by the percentages of leaf and panicle, under adequate climatic conditions, mainly rainfall and temperature. The plants of the second cut had better productivity and development, which explains a higher percentage of stem. The higher percentage of panicles in the first cut can be explained by the low rainfall (24 mm) and the greater amount of brackish water (218.5 mm) in the irrigation during this period, which may have caused stress on the plants, interfering with their development, and promoting the acceleration of their phenological cycle.

Plants with larger stem diameters tend to become more vigorous and productive [40], which was evidenced herein. The stem does not only have the function of supporting leaves and inflorescences but also acts as a structure designed to store soluble solids that are used later in the formation of grains [40].

The higher contents of CP in the first cut can be explained by the lower percentage of stem and a higher percentage of leaves in the first cut compared to the second. The CP contents found in this study are above the minimum (7% based on dry matter) recommended for tropical forages for feeding ruminants [41]. The content of ether extract was influenced by the higher percentage of panicles present in the first cut of pearl millet genotypes because grasses store more fat in the grains.

The salt stress caused by saltwater supplementation in the first cut compared to the second cut directly reflects on the physiological responses of the plants, possibly with the reduction of the leaf blade and alteration in the stem proportion, which may justify the superior results in the second cycle for ADF and lignin concerning the 1st cycle. The structure of lignin is essential for the rigidity of cells and tissues and for resistance to biotic and abiotic stresses. Greater lignification of the cell wall may result in greater protection against lipid peroxidation, because the hydrophobic nature of lignin inhibits the loss of liquid water and/or water vapor to the surrounding environment, attenuating the osmotic stress induced by salinity [42,43].

Higher levels of digestibility are directly related to lower contents of lignin, which justifies the higher means of IVDMD for the first cut. According to Grabber et al. [44], the main tool used by lignin to reduce the digestibility of structural polysaccharides is its interference with the action of enzymes that degrade the cell wall.

Regarding the potassium content, Ketehouli et al. [45] argue that the increase in sodium concentration in the root environment can inhibit the uptake of potassium through the competition between these cations. Sousa et al. [46] evaluated the effect of salinity on nutrients in corn plants and reported that increasing salinity levels in irrigation water reduced the accumulation of K in corn leaves.

The accumulation of calcium in the pearl millet genotypes can be attributed to the use of different levels of gypsum releasing Ca^{2+} and SO_4^{2-} in the soil. Gypsum is a source of Ca (30% CaO), F (0.2%), P (0.7% P_2O_5), and S (17.7%). When applied to the soil surface, S-SO_4^{2-} from its dissolution has the capacity to carry cations to the subsurface layers, alter the toxic forms of aluminum, condition root growth in depth, and consequently explore a larger volume of soil in search of water and nutrients [6,47,48]. This allows the plants to overcome off-season summers and efficiently absorb nutrients applied to the soil, in addition to providing quality to the harvested grains.

The lower absorption of copper in the first cycle was probably the result of the negative interaction of this nutrient with the other elements of planting fertilization. An increased supply of N and P can reduce the uptake of copper by plants. For Bindraban et al. [49], the absorption of N resulted in the alteration of acidity in the rhizosphere, acidifying it when absorbed as NH_4^+ and alkalinizing it when absorbed as NO_3^- . This dynamic can affect the

absorption of other nutrients, in particular the availability of metal ions, which are highly dependent on soil pH.

Organic fertilization with manure may have been decisive in the supply of Mn to pearl millet genotypes. According to Gmach et al. [50], organic matter is one of the main sources of this element in the soil. Plants absorb manganese as Mn^{2+} and the roots are supplied by mass flow and diffusion. These processes are greatly affected by the concentration of the element in the soil solution, which in turn is influenced by pH, redox potential, microbial activity, and organic matter content [51].

5. Conclusions

The pearl millet genotype Bulk 1 BF demonstrated greater tolerance due to its higher panicle proportion, larger panicle size, and improved vegetative growth in the second cut. However, all evaluated pearl millet genotypes exhibited desirable agronomic characteristics and tolerance to irrigation with brackish water, regardless of gypsum application. Therefore, they are suitable for cultivation in semi-arid regions.

Future research should explore the long-term impact of gypsum, different application timings, and the physiological responses of genotypes. Despite these limitations, the findings reinforce the potential of millet for sustainable agricultural systems under saline stress.

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