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Can saline irrigation improve the quality of tomato fruits?

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Abstract

This study aimed to investigate the effect of irrigation with saline water on fruit quality, yield, and plant nutrition of tomato (*Lycopersicon esculentum* Mill.) cultivars. Tomato cultivation was carried out under protected environment conditions in a double row system with drip irrigation performed according to the demand of the plants. Commercial fruit weight, commercial fruit number, fruit yield, absorption of Ca, N, P, S, K, and Mg were all affected by saline irrigation. The leaf Na concentration and the concentration of total phenolic compounds, total titratable acids, total soluble solids, vitamin C, carotenoids, and flavonoids in the fruits were favored from the increase in irrigation salinity. The Na^+ causes a deficiency of Ca, which impairs seed formation in tomato fruits, as Ca is a structural element in the formation of the pollen grain. The Onix genotype had the highest yield, weight, and number of commercial fruits under control and moderate salt stress conditions. Saline water impaired nutrient absorption and improved tomato fruit quality. Under salt stress, tomato plants were able to absorb and translocate large amounts of Na+ to the shoot and even improved the organoleptic quality of fruits, increasing the content of carotenoids, flavonoids, vitamin C, total phenolic compounds, total soluble solids, and total titratable acids of tomato fruits. The clustering analysis was able to show the highest genetic dissimilarity between the group composed of Shanty, Maestrina, and

Abbreviations: CVe, coefficient of experimental variation; CVg, coefficient of genetic variation; CFN, number of commercial fruit; CFW, commercial fruit weight; LCI, leaf chlorophyll index; NCFN, number of noncommercial fruits per plant; NCFW, noncommercial fruit weight; PH, plant height; ROS, reactive oxygen species; TPC, total phenolic compounds; TSS, total soluble solids; TTA, total titratable acid; UPGMA, unweighted pair group method with arithmetic mean; VITC, vitamin C.

Ipa 6 and the group with Sheena, Totalle, and Pizzadoro under salt stress conditions; also, it evidenced the greater stability of these genotypes.

1 | INTRODUCTION

Vegetable intake is essential in human nutrition due to its high nutritional value, rich in vitamins, minerals, antioxidants, and low energy value (Liu et al., 2013). Vegetable production is considerably profitable, even more than grain crops (Oliveira et al., 2019). The vegetable production in Brazil corresponds to about 6% of the Brazilian Gross Domestic Product (GDP) referred to agribusiness, which is explored by small, medium, and large producers, mainly in the vicinities of large urban centers (IBGE, 2015).

Tomato (*Lycopersicon esculentum* Mill.) crops have been one of the fastest-growing vegetable crops in the last 33 yr. One of the main reasons for this growth was the consumption increase. Between 1983 and 2016, per capita consumption increased by 42%, from 14 to 20 kg person^{-1} year^{-1} (FAO, 2018). In 2018, the global tomato area was 4,762 ha, producing around 182 Tg for fresh and processed consumption (FAO, 2019). Tomato fruits contain large amounts of vitamins B and C, Fe, and P. They are consumed fresh in salads or cooked in sauces, soups, and processed into purees, juices, and tomato sauce (ketchup). Canned and dry products are also economically important processed products, serving many markets (Kumar et al., 2020). Lycopene is a carotenoid characterized by being one of the most abundant antioxidant compounds in tomato and gives the characteristic red color to most tomato cultivars on the market. Lycopene and other bioactive compounds are responsible for the antioxidant activity of tomato, which prevents the oxidation of essential molecules caused by free radicals. They significantly contribute to maintaining human health, including preventing heart disease and prostate cancer (Porto et al., 2016). The tomato crop has several cultivars, each with its peculiarity concerning different attributes, such as color, smell, flavor, texture, size, and loci number (Gerszberg et al., 2015).

With the increased demand for tomato, production growth is necessary. Consequently, the excessive use of inorganic fertilizers to obtain higher yields is causing environmental impacts (Hasler et al., 2017), reducing the water quality and damaging the soil and plants (Viol et al., 2017). Salt accumulation in the ground, resulting from inadequate soil management, causes plants to increase the absorption and accumulation of these compounds in their organs, promoting adverse effects on the metabolic and physiological processes of plants (Li et al., 2019; Lofti et al., 2018). Thus, a high salt concentration in the medium hinders water and nutrient absorption of plants due to the low total potential of soil solution and the competition between nutrients and salts for the active sites (Kong et al., 2016). The tomato crop is moderately sensitive to the effects of salts, with electrically conductive of water above 2.5 dS m^{-1}. It is estimated that for each salinity unit increase above this limit, there is a yield reduction of 9.9% (Mass & Hoffman, 1977).

Research on breeding programs has been carried out to improve plant tolerance to salt stress. However, the plant resistance to salt is of great genetic and physiological complexity, limiting the success of the research (Gupta & Huang, 2014). The toxicity effects from salt excess can differ according to species, cultivar, genotype, and variety, achieving superior genotypes with higher yields even under stressful conditions (Oliveira & Steiner, 2017). It is possible to estimate the variables with the most significant positive and negative effects on crop yield through statistical analysis. Based on this, it is possible to select genotypes with greater tolerance to the abiotic stresses effects through indirectly assessed traits (Oliveira et al., 2020). In this sense, the study aimed to investigate the effect of irrigation with saline water on fruit quality, yield, and plant nutrition of tomato cultivars.

2 | MATERIALS AND METHODS

2.1 | Characterization and experimental conduction

The experiment was carried out from July to December 2019, under protected cultivation conditions. Sowing was carried out on 1 July in styrofoam trays containing 128 cells, with a volume of 40 cm^3 filled with commercial substrate Maxxi (Terra Nova) indicated for the production of tomato seedlings with pH (H_2O) = 6.8, pH ($CaCl_2$) = 5.6, organic matter = 200 g dm^{-3}, P (Mehlich^{-1}) = 50.8 mg dm^{-3}, K^+ = 1.04 cmol$_c$ dm^{-3}, Ca^{2+} = 15.51 cmol$_c$ dm^{-3}, Mg^{2+} = 10.45 cmol$_c$ dm^{-3}, H+Al = 4.00 cmol$_c$ dm^{-3}, Al^{3+} = 0.00 cmol$_c$ dm^{-3}, cation exchange capacity = 31.00 cmol$_c$ dm^{-3}, sum of bases = 27.00 cmol$_c$ dm^{-3}, Zn = 22.50 mg dm^{-3}, Cu = 0.20 mg dm^{-3}, Fe = 109.00 mg dm^{-3}, Mn = 54.30 mg dm^{-3}, B = 1.33 mg dm^{-3}, S = 15.20 mg dm^{-3}, base saturation = 87.1%, and electrical conductivity of the extract = 1.23 dS m^{-1}.

The seedlings were transplanted on 7 August, 37 d after sowing, when the seedlings had between two and three true leaves completely expanded. The cultivation was carried out in double fiber cement channels measuring 0.4 × 0.6 ×

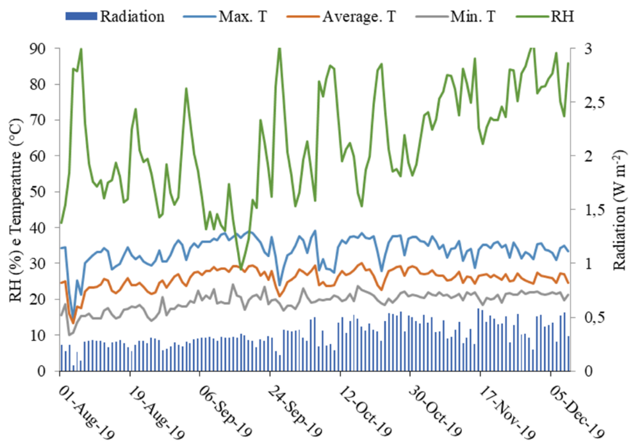

FIGURE 1 Relative air humidity (RH), maximum temperature (Max. T), average temperature (Average T), minimum temperature (Min. T), and radiation during the experiment conduction

Core Ideas

- Saline stress harms tomato yield.
- Salt stress improved the quality of tomato fruits.
- Divergence and genetic stability of tomato genotypes under salt stress.
- Salt stress increased Na and K content in leaves, K improves stress tolerance.
- Saline irrigation harms tomato yield due to the accumulation of salts in the soil.

8.0 m with 1.9 m^3 of soil. The soil used was classified as Neossolo Quartzarenico, with 12.5% clay, 7.5% silt, and 80% sand, pH ($CaCl_2$) = 5.6, organic matter = 33.5 g dm^{-3}, P (resin) = 236 mg dm^{-3}, K^+ = 4.58 $cmol_c$ dm^{-3}, Ca^{2+} = 4.60 $cmol_c$ dm^{-3}, Mg^{2+} = 2.20 $cmol_c$ dm^{-3}, H+Al = 3.30 $cmol_c$ dm^{-3}, Al^{3+} = 0.01 $cmol_c$ dm^{-3}, cation exchange capacity = 14.70 $cmol_c$ dm^{-3}, sum of bases = 11.38 $cmol_c$ dm^{-3}, Zn = 43.7 mg dm^{-3}, Cu = 8.1 mg dm^{-3}, Fe = 40.0 mg dm^{-3}, Mn = 54.0 mg dm^{-3}, B = 2.02 mg dm^{-3}, S = 241.0 mg dm^{-3}, base saturation = 77.5%, and electrical conductivity of the extract = 0.58 dS m^{-1}.

Cultivation was carried out in double rows with a spacing of 0.3 m between plants and 0.4 m between rows of tomato plants, and 1.0 m between double rows with a population of 23,810 plants ha^{-1}. Irrigation and fertigation were carried out through a drip system, with a dripper for each plant. The irrigation management was carried out with a soil moisture measuring device. The tension adopted for the beginning of the irrigation period was recommended for the crop as described by Marouelli et al. (2011). The plants were vertically staked with the aid of string. Cultural treatments such as stakes, sprouts, wiring, and pest and disease control were carried out as recommended for the crop (Silva & Vale, 2007). The topping of the branches was performed when they reached the seventh bunch.

Temperature, radiation, and relative air humidity data were obtained from a meteorological station installed inside the protected environment (Figure 1). Fertilization was carried out with 55 mg dm^{-3} of N, 340 mg dm^{-3} of P, 80 mg dm^{-3} of K, 80 mg dm^{-3} of Ca, 32.5 mg dm^{-3} of Mg, 30 mg dm^{-3} of S, 45 mg dm^{-3} of Si, 2.75 mg dm^{-3} of Zn, 0.5 mg dm^{-3} of B, 1.5 mg dm^{-3} of Mn, 0.25 mg dm^{-3} of Cu. Topdressing fertilizations were also carried out via fertigation with 220 mg dm^{-3} of N, 300 mg dm^{-3} of P, 140 mg dm^{-3} of K, and 250 mg dm^{-3} of Ca during the entire cycle divided into 15 weekly applications. From the flowering period onwards, weekly applications of 0.0015% N and 0.002% Ca were carried out on the leaves to supply the need for Ca and avoid crop physiological disturbances. Substrate samples were randomly collected in the plots after harvest to characterize the chemical traits of the substrate and its salination increase in the form of electrical conductivity of the extract at the three irrigation salinity levels (Table 1).

2.2 | Treatments and experimental design

The experimental design was completely randomized with four replications in a 3 × 12 factorial scheme. The first factor was composed of three salinity levels of irrigation water: control, using water without adding NaCl, with electrical conductivity of 0.02 dS m^{-1}; moderate salinity, with electrical conductivity of 1.5 dS m^{-1}; and severe salinity, with electrical conductivity of 3.0 dS m^{-1}. Water preparation with different salinity levels was carried out according to the equation obtained in a previous study: CE = 0.1676 + 2.0193 Q^{NaCl} (R^2 = .999; P < .01), where EC = electrical conductivity of the solution (dS m^{-1}), and Q^{NaCl} = amount of NaCl (g L^{-1}). The second factor was composed of 12 tomato cultivars (Table 2).

2.3 | Assessments

The following morphological traits were evaluated: the number of commercial fruits per plant (CFN), number of noncommercial fruits per plant (NCFN), plant height (PH), commercial fruit weight (CFW), noncommercial fruit weight (NCFW), plant height (PH), and fruit yield (YIELD). For both groups, the fruits were considered as commercial fruits when the transverse diameter was above 40 mm. Fruits with transverse diameter below 40 mm were considered noncommercial. The fruit yield (kg ha^{-1}) was determined from the production of commercial fruits per plant (kg $plant^{-1}$) multiplied

TABLE 1 Chemical characteristics of soil irrigated with three salinity levels at the end of the experiment

Characteristic	Control treatment (without saline water)	Moderate salinity	Severe salinity
pH	6.4	6.3	6.9
P_{resin}, mg dm^{-3}	152	170	151
S, mg dm^{-3}	142	140	133
OM, g dm^{-3}	28	28	27
K, cmol$_c$ dm^{-3}	10.5	12.7	12.7
Ca, cmol$_c$ dm^{-3}	25.0	15.3	13.8
Mg, cmol$_c$ dm^{-3}	2.8	3.3	2.6
Al, cmol$_c$ dm^{-3}	0.0	0.0	0.0
Al + H, cmol$_c$ dm^{-3}	1.1	1.1	1.2
SB, cmol$_c$ dm^{-3}	28.9	19.8	17.6
CEC, cmol$_c$ dm^{-3}	30.0	21.3	18.7
AS, %	0.0	0.0	0.0
BS, %	96	93	94
EC, dS m^{-1}	0.35	1.05	2.42
B, mg dm^{-3}	0.64	0.77	0.79
Cu, mg dm^{-3}	13.7	12.0	14.9
Fe, mg dm^{-3}	34.0	30.0	40.0
Mn, mg dm^{-3}	3.6	4.0	5.5
Zn, mg dm^{-3}	21.6	22.5	22.5

Note. AS, aluminum saturation; BS, base saturation; CEC, cation exchange capacity; EC, electric conductivity; H + Al, potential acidity; OM, organic matter; SB, sum of bases.

TABLE 2 Cycle, growth habit, and group or type of the 12 tomato cultivars evaluated

Cultivar	Cycle	Growth habit	Group/type
Santa Clara 5800	110	Indeterminate	Salad
Coração de Boi	120	Indeterminate	Salad
Ipa 6	115	Determinate	Salad
Maestrina	125	Indeterminate	Salad
Onyx	125	Indeterminate	Salad
Dominador	120	Indeterminate	Salad
Shanty	120	Determinate	Italian
Sheena	115	Determinate	Italian
Pizzadoro	125	Indeterminate	Italian
Totalle	120	Indeterminate	Italian
Sperare	115	Indeterminate	Italian
Pizzamonty	120	Indeterminate	Italian

by the estimated population of one cultivation hectare (23,810 plants ha^{-1}). The leaf chlorophyll index (LCI) was measured on four tomato plants per plot at flowering using a portable nondestructive chlorophyll Falker meter (ClorofiLOG–model CFL–1030, Falker). When the plants had the most fruits close to harvest (complete maturation), all leaves of the plant were collected and dried at 60 ˚C for 72 h. The dried samples were ground in a Wiley-type mill with a 1-mm opening sieve and packed in identified plastic bags. The leaf contents of N, P, K, S, Ca, Mg, Zn, and Na were determined according to descriptions by Malavolta et al. (1997).

Five ripe fruits (commercial fruits) per plant of each treatment were harvested for organoleptic analyses. The fruit was crushed with the aid of a mixer, leaving the tomato pulp completely homogeneous. Chemical analyzes of the tomato fruit pulp were performed. For total titratable acidity (by volumetry with indicator and expressed in grams of citric acid, calculated considering the equivalent of a gram) evaluation, 10 ml of tomato juice was transferred to a 250 Erlenmeyer ml and added 90 ml of distilled water. This solution was titrated with standard 0.1 M sodium hydroxide solution until the color of the solution turned deep pink. Vitamin C was determined by the iodometry method, 25 ml of tomato juice was transferred to a 250 ml Erlenmeyer, and 25 ml of distilled water was added, with the addition of 1 ml of 1% starch solution (indicator). This solution was titrated with 1% iodine solution (which reacts with starch to form iodide) until the solution turned brown (IAL, 2008). The determination of fruit contents of carotenoid and flavonoid was performed in a UV-Vis spectrophotometer (FEMTO model 800 XI) according to analytical separation methodology and extraction of compounds with organic solvents (Nagata & Yamashita, 1992; Rodriguez-Amaya & Kimura, 2004) and flavonoids (Awad et al., 2000). To determine the content of total phenolic compounds, the

TABLE 3 Summary of ANOVA of 12 genotypes of tomato under three salinity levels of irrigation water

Source of variation	Mean square NCFN	CFN	NCFW	CFW	PH	YIELD	LCI
Genotype (G)	247.6**	32.02**	701.8**	1,456.44**	0.75**	2,949.9**	56.26**
Salinity (S)	1,871.9**	424.30**	4,305.3**	8,958.9**	1.15**	34,458.4**	2,640.4**
G × S	93.43**	4.06**	24.70**	275.0**	0.85**	910.3**	29.04**
Block	1.61	0.68	4.18	39.52	0.08	17.50	7.58*
Error	4.03	4.26	4.28	73.25	0.08	29.48	1.33
Var G	60.91	6.94	174.3	345.8	0.17	730.1	–
h^2	98.37	86.70	99.39	94.97	89.33	99.00	–
CVe, %	17.98	6.38	8.21	16.70	18.94	12.95	2.72
CVg, %	140.9	17.49	231.7	124.4	57.99	129.5	–
CVg/CVe	7.84	2.74	28.24	7.45	3.06	10.00	–
	N	**P**	**K**	**Ca**	**Mg**	**S**	**Na**
Genotype (G)	17.51**	18.65**	191.4**	51.34**	3.76**	16.20**	149.7**
Salinity (S)	157.4**	31.23**	17.51**	711.38**	35.59**	238.9**	1,0221**
G × S	10.06**	2.41**	160.0**	43.79**	1.24**	17.11**	124.1**
Block	5.70	0.01	0.77	1.44	0.24	1.03	2.69
Error	2.05	0.01	1.52	1.75	0.23	1.05	1.76
CV, %	5.48	2.04	3.78	4.57	6.73	7.51	6.76
	Zn	**TPC**	**FLA**	**CAR**	**VITC**	**TSS**	**TTA**
Genotype (G)	5534**	3222**	1980**	0.007**	0.55**	11.19**	7.51**
Salinity (S)	10,085**	3961**	4004**	0.006**	13.41**	114.1**	100.1**
G × S	1,054**	43.86**	35.72**	0.0002**	0.27**	2.36**	9.83**
Block	7.56	1.84	5.19	0.00007	0.02	0.09	0.19
Error	17.79	1.44	2.17	0.00002	0.02	0.04	0.12
CV, %	4.68	2.24	3.56	11.55	6.78	3.36	4.07

Note. CAR, carotenoids; CFN, number of fruits commercial; CFW, commercial weight fruit; CVe, experimental variation coefficient; CVg, coefficient of genetic variation; FLA, flavonoids; h^2, heritability; LCI, leaf chlorophyll index; NCFN, noncommercial fruits; PH, plant height; TPC, total phenolic compounds; TSS, total soluble solids; TTA, total titratable acids; Var G, genetic variance; YIELD, fruit yield.

*Significant at .05 probability by *F* Test. **Significant at .01.

procedure was according to Wettasinghe and Shahidi (1999), using the Folin–Ciocauteau spectrophotometric method.

2.4 | Statistical analysis

The data from all variables presented normal distribution and homogeneous variances. They were submitted to analysis of variance, and the *F* test tested the significance of the mean squares at the .05 probability level. The means from tomato cultivars were grouped by the Scott and Knott (1974) clustering algorithm at the .05 probability level. The means from different salinity levels were compared by the Tukey test at the .05 probability level.

Heritability (h^2), coefficient of experimental variation (CVe), coefficient of genetic variation (CVg), and CVg/CVe ratio were estimated according to Cruz and Regazzi (1997). The data from all variables were submitted to correlation analysis, and the results were expressed in a heatmap. A dendrogram of dissimilarity pattern obtained by the unweighted pair group method with arithmetic mean (UPGMA) based on the Gower distance among tomato genotypes was elaborated for each salinity level of irrigation water.

3 | RESULTS

3.1 | Tomato production irrigated with saline water

The genotypes, salinity level, and interaction between factors significantly influenced all the evaluated traits ($P \leq .01$), with a coefficient of experimental variation (CVe) below 20%, showing the high precision of results even under stressful conditions. The number of commercial fruits (CFN) and the plant height (PH) had the lowest genetic variation among the

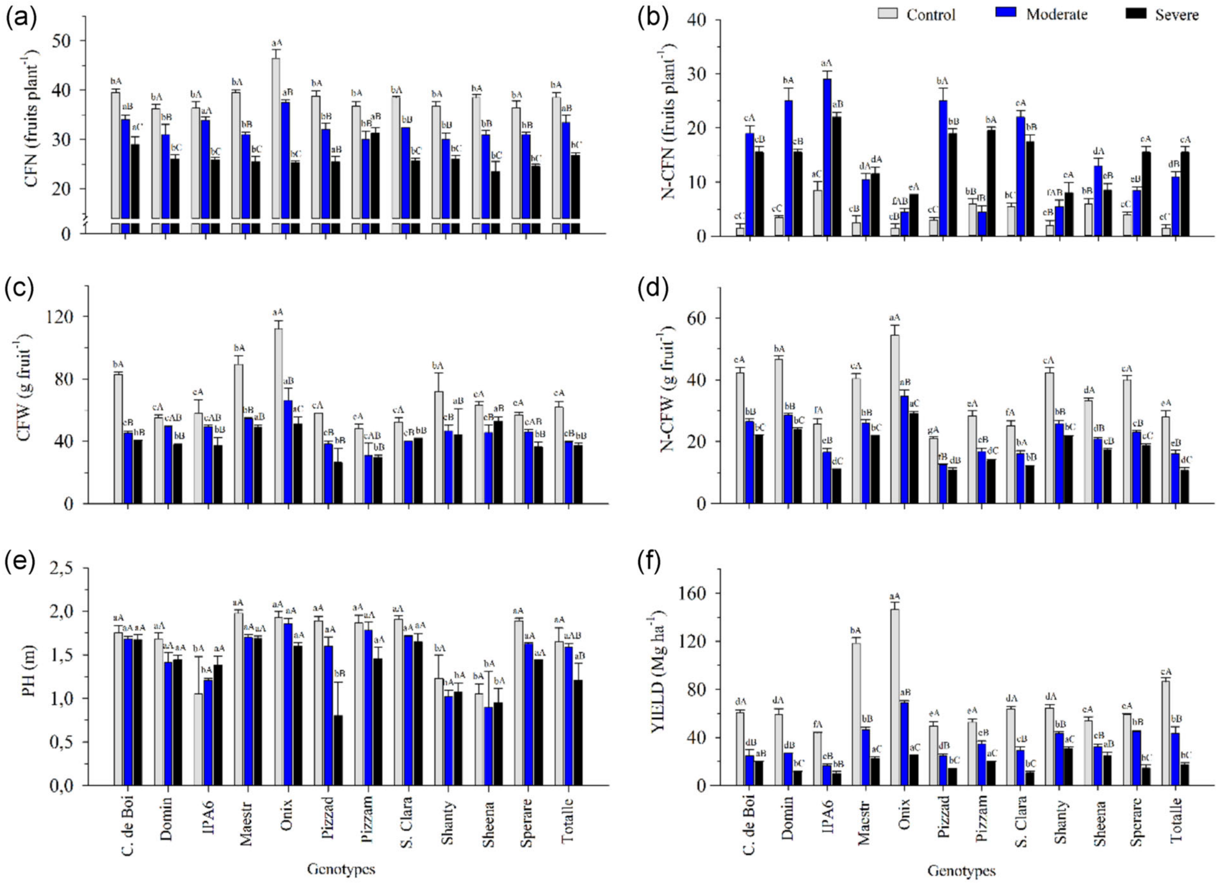

FIGURE 2 (a) Commercial fruits number per plant (CFN), (b) noncommercial fruits number per plant (NCFN), (c) commercial fruit weight (CFW), (d) noncommercial fruit weight (NCFW), (e) plant height (PH), and (f) yield of fruits (YIELD) of 12 genotypes of tomato under three salinity levels of irrigation water. Means followed by the same lowercase letter in bars of the same color within each salinity level belong to the same group by the Scott and Knott (1974) cluster test with .01 probability. Means followed by the same uppercase letter in bars with different colors within each genotype differ by the Tukey test at .01 probability

genotypes. On the other hand, the noncommercial fruits weight, commercial fruits weight, and fruit yield had high genetic variation. All traits had high heritability above 86%. The coefficient of genetic variation (CVg) ranged from 17 to 231%; the highest CVg was found in the NCFW, an undesirable trait in tomato production (Table 3).

The CFN was found under control treatment conditions for all genotypes except Ipa 6. The CFN of this genotype was not affected by the moderate salinity level. Under control treatment conditions, the Onix genotype stood out compared to the other genotypes regarding CFN. The group composed of Coração de Boi, Ipa 6, Onix, and Totalle genotypes had higher CFN than the other genotypes under moderate salinity conditions. Under severe salinity conditions, Coração de Boi and Pizzamonty genotypes had the highest CFN (Figure 2a). The number of noncommercial fruits (NCFN) was lower in the control treatment than other salinity levels. Coração de Boi, Dominador, Ipa 6, Maestrina, Pizzadoro, Santa Clara, and Sheena had the highest NCFN under moderate salinity level conditions. Under severe salinity conditions, Pizzamonty, Sperare, and Totalle had the highest NCFN. Ipa 6 had the highest NCFN at all salinity levels (Figure 2b).

The highest weight of commercial fruits (CFW) in all genotypes concerning severe salinity level (Figure 2c) was verified in the control treatment. The same result was observed for the weight of noncommercial fruits (NCFW); under control treatment conditions, the genotypes had higher NCFW than the other two salinity levels (Figure 2d). Onix had the highest CFW under control and moderate salinity conditions. However, under severe salinity, the highest CFW was found in Maestrina, Onix, Shanty, and Sheena. The highest NCFW was found in the Onix genotype regardless of the salinity level of the irrigation water (Figure 2).

Only the Pizzadoro and Totalle genotypes had the PH affected by the severe salinity level. Under control and moderate salinity conditions, Ipa 6, Shanty, and Sheena had the lowest PH. Under severe salinity, Pizzadoro, Totalle, Shanty, and Sheena genotypes had the lowest PH (Figure 2e). The highest YIELD was found in the control treatment concerning

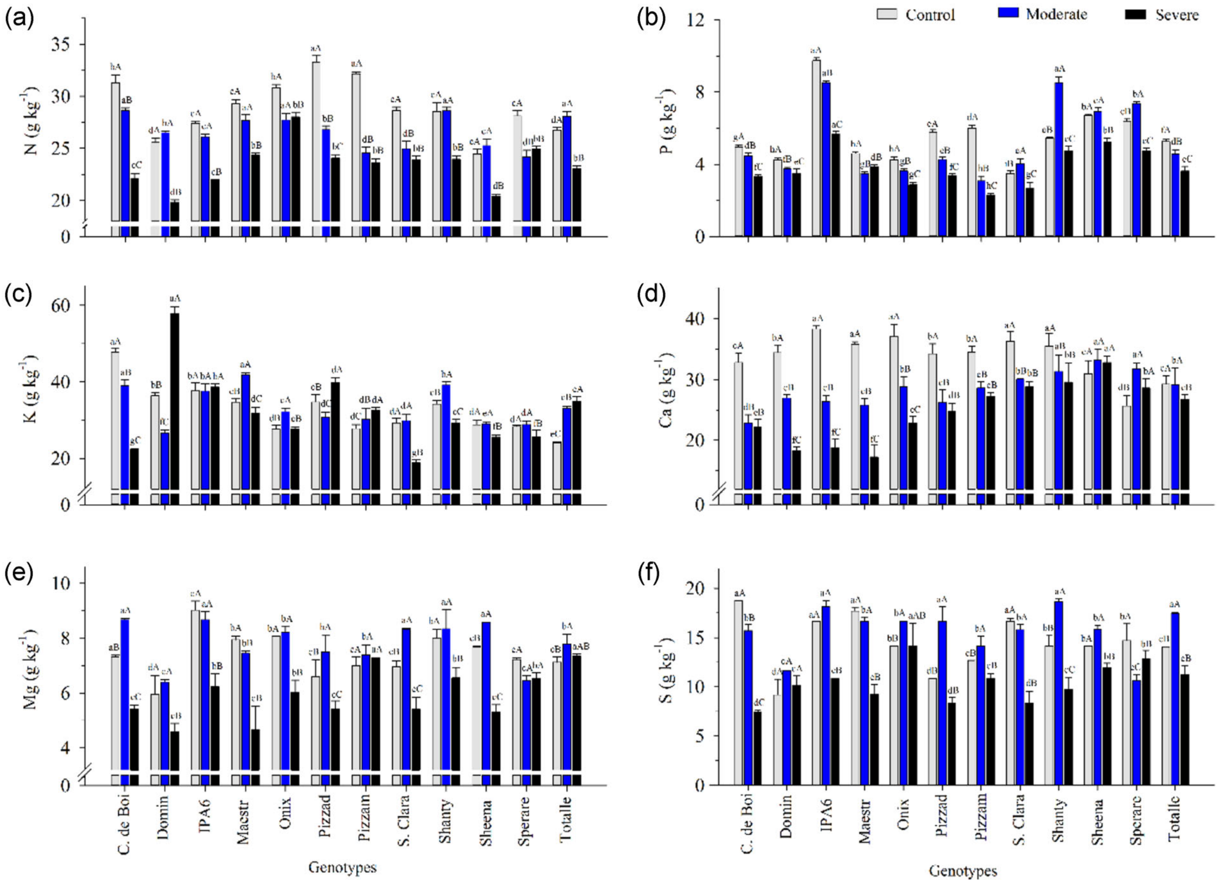

FIGURE 3 Leaf content of (a) N, (b) P, (c) K, (d) Ca, (e) Mg, and (f) S of 12 genotypes of tomato under three salinity levels of irrigation water. Means followed by the same lowercase letter in bars of the same color within each salinity level belong to the same group by the Scott and Knott (1974) cluster test with .01 probability. Means followed by the same uppercase letter in bars with different colors within each genotype differ by the Tukey test at .01 probability

the other salinity levels. The Onix genotype had the highest YIELD under control and moderate salinity conditions. However, under severe salinity level, Onix Maestrina, Pizzamonty, Coração de Boi, Shanty, and Sheena had the highest YIELD (Figure 2e).

3.2 | Salt stress affects plant nutrition

Under the control treatment conditions, the Pizzadoro, Pizzamonty, and Onix genotypes had the highest LCI and leaf N concentration. Under moderate salinity, the highest LCI and N were verified in Coração de Boi, Maestrina, Onix, Shanty, and Totalle. Under severe salinity, Onix had the highest LCI and N (Figure 3a). The increase in irrigation water salinity affected the leaf chlorophyll index (LCI); only Coração de Boi and Dominador genotypes did not have LCI affected by moderate salinity. The other genotypes were affected by moderate and severe salinity level (Figure 4a).

Leaf content of P was higher under the control treatment than severe salinity. On the other hand, Santa Clara, Shanty, and Sperare genotypes had a higher P under moderate salinity than control and severe salinity conditions. Ipa 6 had the highest P under the control treatment and severe salinity. Under moderate salinity, the genotypes with the highest P were Ipa 6 and Shanty (Figure 3b). The leaf content of K was higher in the genotypes Coração de Boi, Santa Clara, Sheena, and Sperare under the control treatment than severe salinity conditions. Maestrina, Onix, Santa Clara, Shanty, Sheena, and Sperare had higher K under moderate than severe salinity. The Dominador, Pizzadoro, Pizzamonty, and Totalle genotypes had higher K under severe salinity than other salinity levels (Figure 3c).

Leaf content of Ca was higher in all genotypes, except Sheena and Sperare, under the control treatment than severe salinity (Figure 3d). Ipa 6 had the highest Mg content under the control treatment. Under moderate salinity, Ipa 6, Shanty, Sheena, Coração de Boi, Onix, and Santa Clara had the highest Mg. Pizzamonty and Totalle had the highest Mg under severe salinity. The severe salinity provided lower leaf content of Mg than the control treatment (Figure 3e). Severe salinity impaired the uptake and translocation of S in all genotypes,

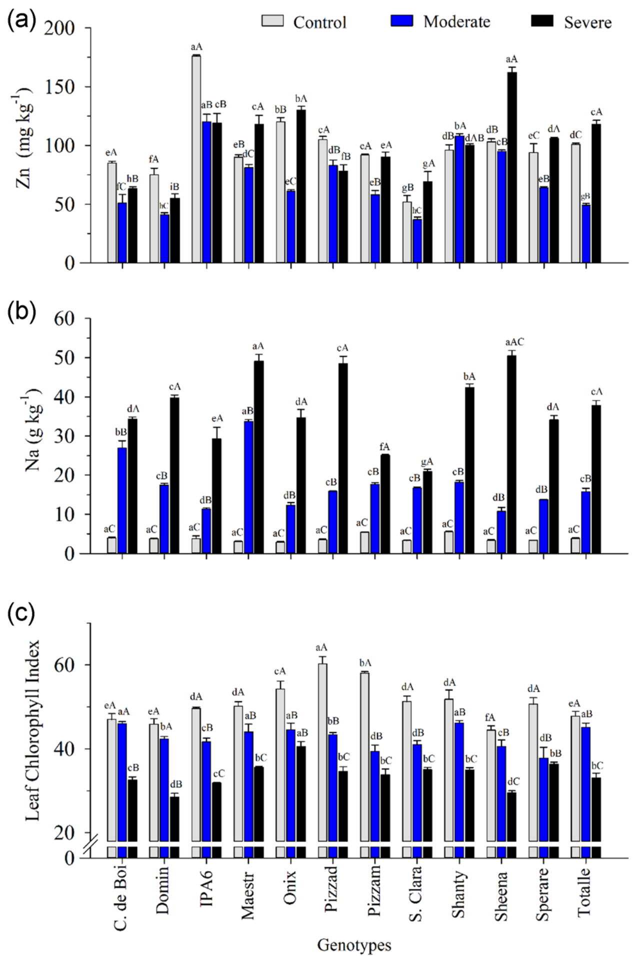

FIGURE 4 Leaf content of (a) Zn, (b) Na, and (c) leaf chlorophyll index of 12 genotypes of tomato under three salinity levels of irrigation water. Means followed by the same lowercase letter in bars of the same color within each salinity level belong to the same group by the Scott and Knott (1974) cluster test with .01 probability. Means followed by the same uppercase letter in bars with different colors within each genotype differ by the Tukey test at .01 probability

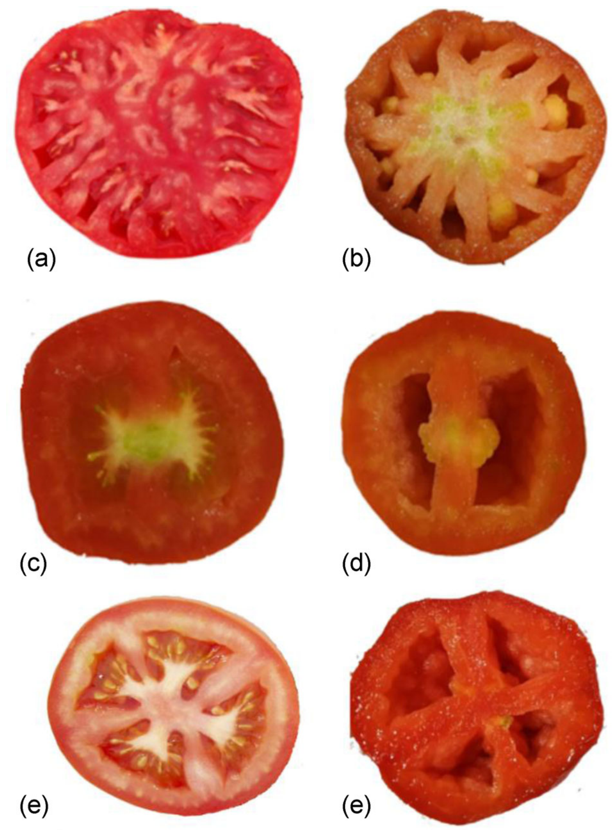

FIGURE 5 Tomato fruit of Coração de Boi genotype with seeds under control treatment: (a) without saline water and (b) without seeds under salinity conditions; tomato fruit of Ipa 6 genotype with seeds under control treatment: (c) without saline water and (d) without seeds under salinity conditions; tomato fruit of Shanty genotype with seeds under control treatment: (e) without saline water and (f) without seeds under salinity conditions

except for Dominador. Onix had the highest S content under severe salt stress. Santa Clara, Ipa 6, Maestrina, and Coração de Boi had the highest S under the control treatment. Under moderate salinity, Pizzadoro, Totalle, Ipa 6, and Shanty had the highest S (Figure 3f).

The Sheena genotype had the highest Zn content in the leaves under severe salinity conditions. Ipa 6 had the highest Zn under control and moderate salinity conditions. The Coração de Boi, Dominador, Ipa 6, Pizzadoro, and Pizzamonty had Zn harmed by severe salinity. On the other hand, the other genotypes had Zn absorption favored by severe salinity (Figure 4b). The severe salinity impaired the absorption and translocation of Ca to the leaves in all genotypes except for Sperare and Sheena. This effect is the opposite concerning Na content in the leaves, where the highest content of Na occurred under severe and moderate salinity (Figure 4c).

There was no difference in Na content between the genotypes under the control treatment. Under moderate salinity, Maestrina and Coração de Boi had the highest leaf content of Na. On the other hand, under severe salinity, the highest Na was verified in Maestrina, Pizzadoro, and Sheena (Figure 4c).

The excess of Na absorbed by the tomato plant was translocated to shoots and fruits, managing to inhibit the formation of tomato seeds, even with the formation of fruit (low transport of water to fruit). It occurred due to Na^+ impairing the absorption of Ca, which is a component of the cell wall, pollen grain, and pollen tube. Coração de Boi had normal fruit formation with the presence of seeds under control conditions (Figure 5a), but fecundity is impaired by salt, inhibiting seed formation in fruits under salinity conditions (Figure 5b). The same was observed for Ipa 6 and Shanty under control treatment (Figure 5c,e) and salinity conditions (Figure 5d,f).

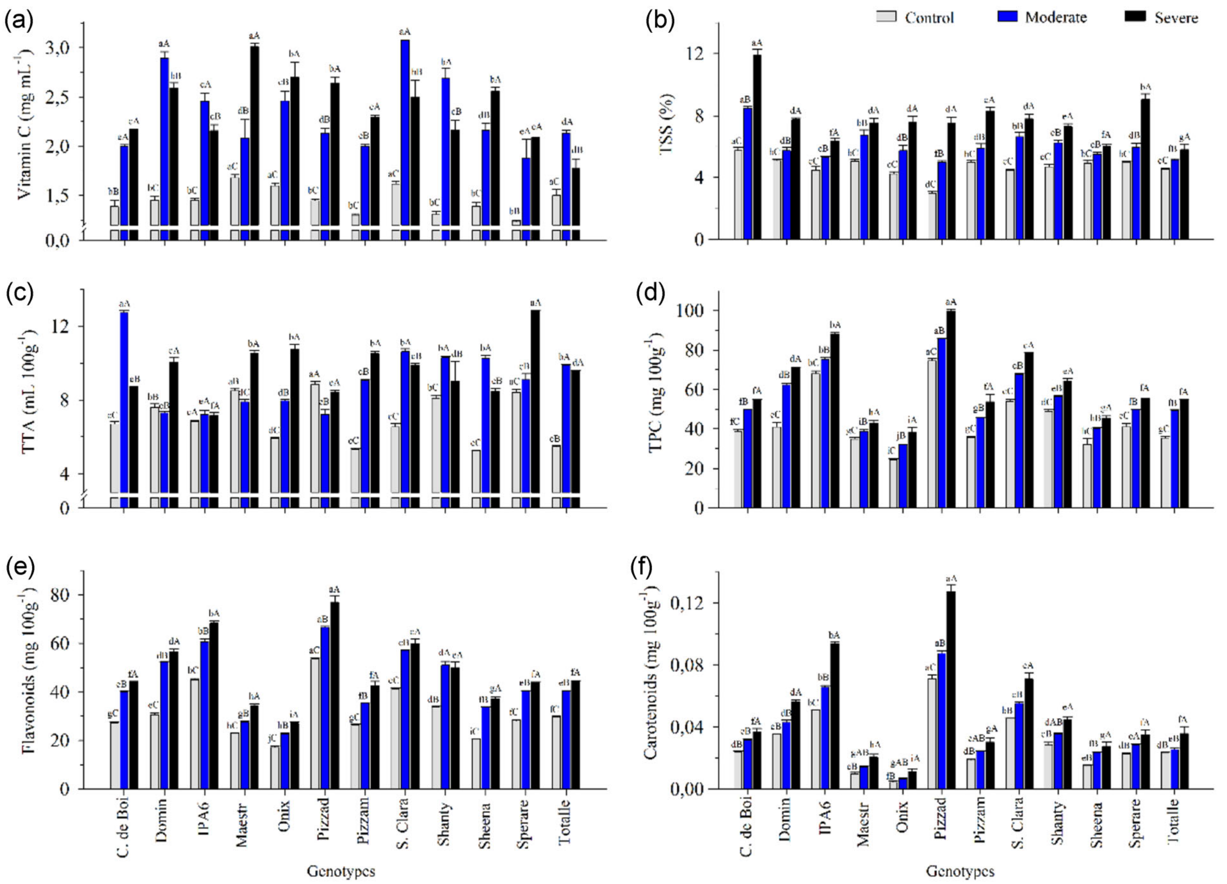

FIGURE 6 (a) Content of vitamin C, (b) total soluble solids, (c) total titratable acids, (d) total phenolic compounds, (e) flavonoids, and (f) carotenoids in fruits of 12 genotypes of tomato under three salinity levels of irrigation water. Means followed by the same lowercase letter in bars of the same color within each salinity level belong to the same group by the Scott and Knott (1974) cluster test with .01 probability. Means followed by the same uppercase letter in bars with different colors within each genotype differ by the Tukey test at .01 probability

3.3 | Quality of tomato fruits under salt stress

The Santa Clara, Dominador, and Shanty genotypes had the highest vitamin C content under control treatment conditions. Dominador, Santa Clara, Sheena, Maestrina, Pizzadoro, and Onix had the highest vitamin C content in the fruits under moderate salinity conditions. Maestrina, Onix, Totalle, and Santa Clara had higher vitamin C under severe salt stress conditions. The salinity of irrigation water increased the vitamin C levels of the fruits in all genotypes (Figure 6a).

Pizzadoro had the lowest total soluble solids (TSS) under control treatment conditions. Under severe salinity conditions, Coração de Boi had the highest TSS content. Fruits from plants under severe salinity conditions had higher TSS than fruits under control for all cultivars, except for Totalle. Salt stress increased fruit sweetness. Coração de Boi had the highest TSS at all salinity levels; this may be a characteristic of this genotype, which benefited from the salinity of irrigation water, increasing the accumulation of TSS in the fruits by reducing the amount of salt in the water (Figure 6b). The total titratable acids (TTA) increased in all genotypes under salinity conditions. Pizzadoro, Maestrina, Shanty, Sperare, and Dominador had the highest TTA under control treatment conditions. Under moderate salinity conditions, Coração de Boi, Santa Clara, Shanty, Sheena, and Totalle had the highest TTA. Under severe salinity conditions, Sperare, Onix, Pizzamonty, Maestrina, and Dominador had the highest TTA (Figure 6c).

Pizzadoro, Ipa 6, Santa Clara, Dominador, and Shanty had the highest total phenolic compounds (TPC) at all salinity levels. Moderate and severe salinity of irrigation water increased TPC in all genotypes (Figure 6d). With the increase of salinity level, there was a rise of flavonoids and carotenoids contents regardless of the genotype used. Pizzadoro, Ipa 6, Santa Clara, Shanty, and Dominador had the highest contents of flavonoids and carotenoids in the fruits (Figure 6e,f).

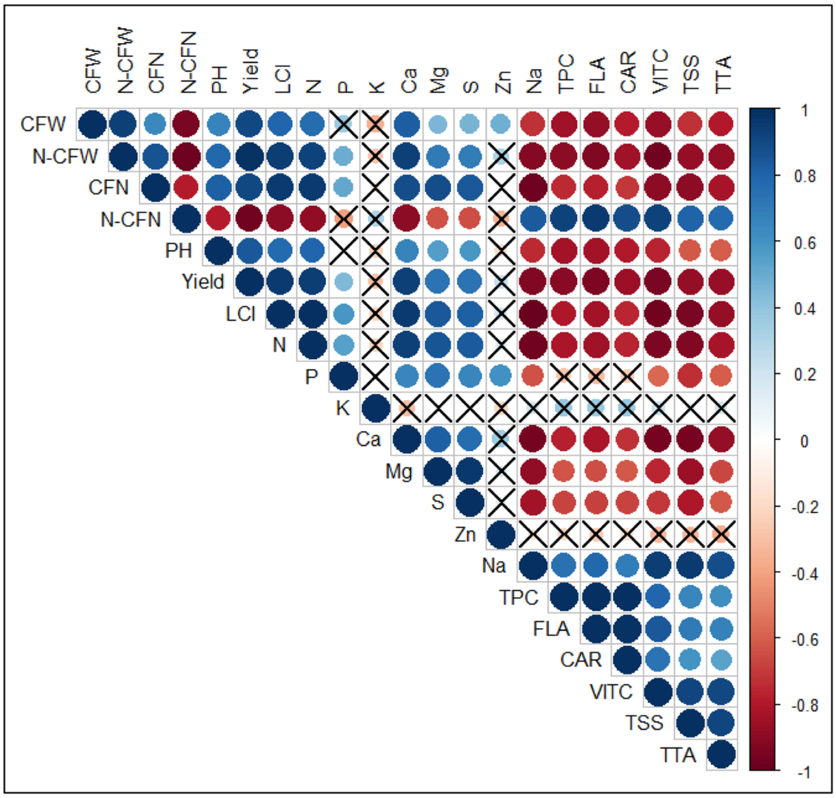

FIGURE 7 Heatmap of the Pearson correlation coefficients obtained from variables analyzed in tomato genotypes in response to salt stress. X Indicates no significant correlation ($P < .05$) for the traits: commercial fruits weight (CFW), noncommercial fruits weight (NCFW), commercial number of fruits per plant (CNF), noncommercial number of fruits per plant (NCNF), plant height (PH), yield fruit (Yield), leaf chlorophyll index (LCI), leaf concentration on N, K, P, Ca, Mg, S, Zn, and Na, total phenolic compounds (TPC), flavonoid content (FLA), carotenoid content (CAR), vitamin C (VITC), total soluble solids (TSS), and titratable total acidity (TTA)

3.4 | Correlations between traits and cluster analysis

Negative and significant correlations were found between NCFN and CFW, NCFW, CFN, PH, Yield, LCI, N, Ca, Mg, and S. However, the NCFN had a positive correlation with Na, TPC, FLA, CAR, VITC, TSS, and TTA. The variables Na, TPC, FLA, CAR, VITC, TSS, and TTA have a negative and significant correlation with CFW, NCFW, CFN, PH, Yield, LCI, N, Ca, Mg, and S, and positive with each other. There was a positive and significant correlation between the CFW, NCFW, CFN, PH, Yield, LCI, N, Ca, Mg, and S. The correlation was positive and significant between P and NCFW, CFN, Yield, LCI, N, Ca, Mg, S, and Zn, and negative with Na, VITC, TSS, and TTA (Figure 7).

Sheena, Totalle, Onix, and Pizzadoro composed a similarity group with high dissimilarity from the Maestrina and Shanty genotypes. Maestrina and Shanty had high similarity with Pizzamonty under control treatment conditions (Figure 8a). Under moderate salinity conditions, the group composed of Sheena, Totalle, and Pizzadoro had a high dissimilarity from the group composed of Ipa 6, Maestrina, and Shanty. Which, in turn, has a greater similarity with Pizzamonty. Also, the genotypes Santa Clara, Sperare, Dominador, and Onix had greater similarity with the group composed of Sheena, Totalle, and Pizzadoro (Figure 8b). The group composed of Sheena, Pizzadoro, and Totalle had a high dissimilarity from the Onix genotype, which had greater similarity with Maestrina, Shanty, and Ipa 6 under severe salinity conditions (Figure 8c).

4 | DISCUSSION

The number of commercial fruits was affected by the severe salinity level in all genotypes. Only Ipa 6 did not have the number of commercial fruits affected by this salinity level; the others genotype were harmed at the moderate salinity level. On the other hand, the smallest number of noncommercial fruits was verified in all genotypes in the control treatment compared to the severe salinity. Salinity affects the number of tomato fruits by increasing the rate of flower abortion, reducing egg fertility, and increasing pollen grain infertility (Barnabas et al., 2008). The Onix genotype had the highest number of commercial fruits under the control treatment. Under moderate salinity, Totalle, Onix, Ipa 6, and Coração de Boi had the largest number of commercial fruits. The Coração de Boi and Onix genotypes were less affected by severe salinity with more fruits than the other genotypes. Ipa 6 had the largest number of noncommercial fruits at all salinity levels; it means that this genotype tends to have a higher number of fruits than it can sustain (Figure 2). Some authors mention that depending on the species and variety of plants, there is significant genetic variability regarding salinity tolerance (Ashraf & Foolad, 2007).

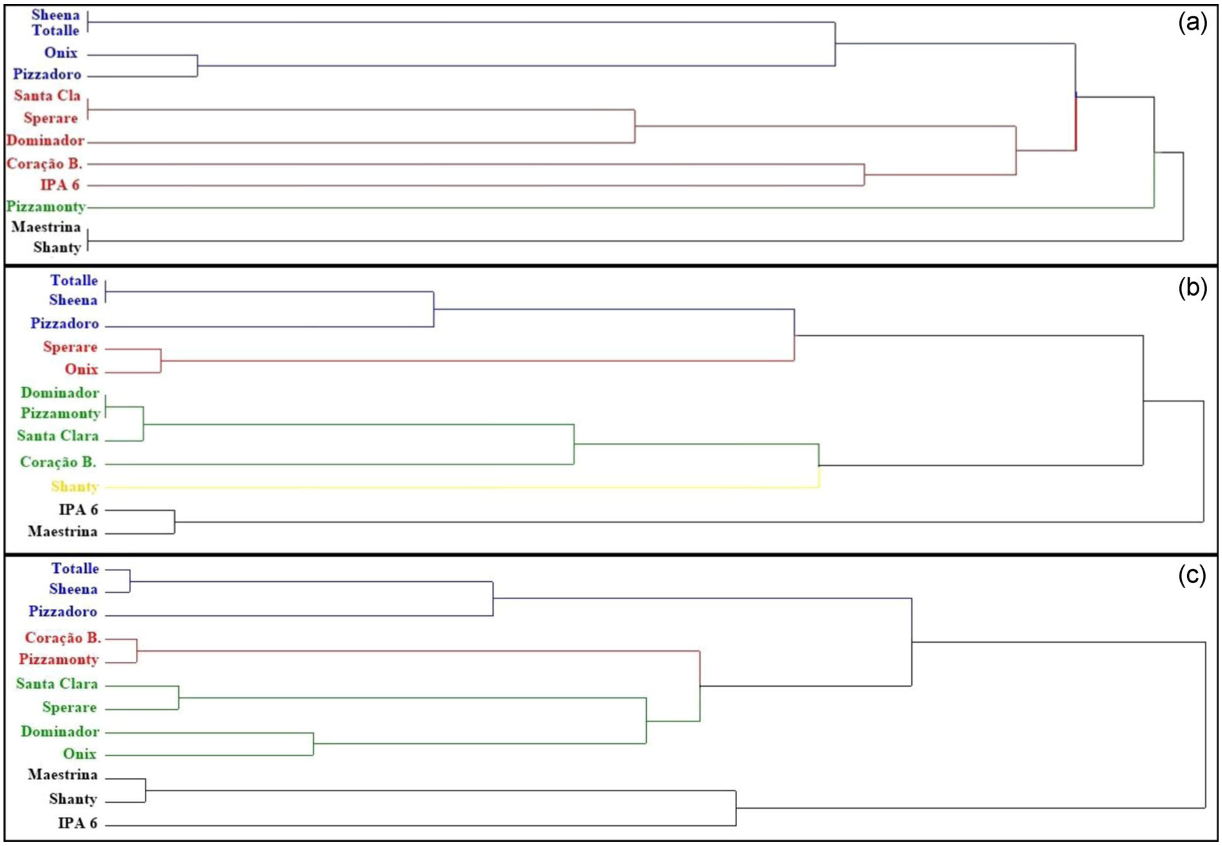

FIGURE 8 Dendrogram of dissimilarity pattern obtained by the unweighted pair group method with arithmetic mean (UPGMA), based on the Gower distance of 12 tomato genotypes under control treatment conditions: (a) without salinity, (b) the moderate salinity level of irrigation water, and (c) severe salinity level of irrigation water

The CFW was higher under control conditions than severe salinity for all genotypes. It was also higher than under moderate salinity conditions for the Coração de Boi, Maestrina, Onix, Pizzadoro, Santa Clara, Shanty, Sheena, and Totalle. The NCFW was affected by salinity regardless of the level in all genotypes. The highest CFW under the control and moderate salinity levels was found in the Onix genotype. Also, Onix had the highest NCFW at all saline levels. Under severe salinity, the highest CFW was verified in the Maestrina and Onix genotypes (Figure 2). Fruit weight is mainly affected by the difficulty in absorbing water and nutrients caused by lower soil water potential, resulting in lower photosynthetic rates, lower transpiration, and an imbalance in nutrient absorption due to the low amount of water absorbed (Alves et al., 2018). The excess of Na^+ in the soil reduces mainly the absorption of Ca^{2+} and K^+, nutrients responsible for structuring the cell wall and water balance of plants, respectively (Domingues et al., 2016).

The fruit yield was harmed by the use of water with severe salinity, which can be attributed to the nutritional imbalance of the plant, caused by the effect of the imbalance in the cation absorption (Figure 2f). Consequently, a higher Na concentration was observed in the plants under salinity conditions. There was no difference between the genotypes (Figure 2e) under the control treatment. The leaf concentration of P, K, N, Mg, and Ca decreased under salinity conditions, except for the Sperare genotype, which increased Ca content under salinity. The K content has its absorption impaired with excess Na from the soil.

On the other hand, the Dominador, Pizzamonty, Pizzadoro, and Totalle were able to increase K absorption in the presence of Na, possibly by surpassing the tolerance threshold for Na saline stress, growing and producing under such conditions. On the other hand, severe salinity promoted greater Zn absorption in Maestrina, Onix, Pizzamonty, Santa Clara, Shanty, Sheena, Sperare, and Totalle genotypes. In contrast, the other genotypes had Zn uptake and translocation impaired by the salinity (Figures 3 and 4). The presence of NaCl in the soil causes nutritional disturbances in plants because Na hinders and/or inhibits the other cation absorption by the roots, causes physiological disorders due to the high ionic concentration, and the toxic effect of chloride ions, which is still harmful to other cells that make up the plant (Hajlaoui et al., 2010). The use of solutions with high NaCl concentrations can induce oxidative stress in plant cells and consequently increase reactive oxygen species (ROS) production

(Alharby et al., 2016). The ROS are highly reactive and can induce lipid peroxidation, causing damage to enzymes, proteins, and nucleic acids (Duman & Koca, 2014).

The excess of Na impaired the uptake of Ca by the plants, which reduced the formation of seeds in the fruits; this was because Ca is a component of the cell wall, pollen grain, and pollen tube. When the genotype can reduce the loss of fruits per plant, it may be creating a source of resistance to salinity, which, even with stress-induced sterility, may be developing the embryo without the presence of seeds (Wilkinson et al., 2018). During cultivation, this report was observed when tomato fruits under severe salinity conditions had fruits without seeds (Figures 5b,d,f). The same genotypes under the control treatment (without salinity) had normal seed production (Figure 5a,c,e). Pollen viability is one of the factors studied to confer plant tolerance to the effects of salt stress, as pollen infeasibility can reduce yields due to the abortion of reproductive organs (Razzaq et al., 2019).

Fruit TSS were higher when tomato plants were under moderate and severe salinity effects. The salinity increased fruit sweetness. The TTA, TSS, and vitamin C were higher under severe salinity level of the irrigation water. This result is due to the low absorption of water and nutrients by the roots, in response to the osmotic effect of the salt present in the soil solution, and also to the difficulty in translocating solute to the drains (fruits) (Dorai et al., 2001). There may be changes in the metabolism of the tomato plant, increasing the soluble solids content. Even high concentrations of salt in the irrigation water can stimulate the defense system of plants, leading to the accumulation of secondary metabolites in different plant tissues (Borghesi et al., 2011; Martínez et al., 2012), in addition to vitamin C in plants under moderate salinity (Paiva et al., 2018).

The content of carotenoids, flavonoids, and total phenolic compounds was favored by increasing the salinity of irrigation water in all genotypes. These components are closely linked to oxidative protection under stressful conditions (Figure 6). The increase of carotenoids in fruits can protect plants against oxidative stress. It has a photoprotective function. It is a precursor of vitamin A in fruits and provides a pleasant and intense aroma (Uenojo et al., 2007). Carotenoids, flavonoids, and total phenolic compounds are related to fruit pigmentation, the antioxidant system, and improve the quality of tomato fruit produced (Aghofack-Nguemezi & Schwab, 2014). Lycopene is a carotenoid characterized by being one of the most abundant antioxidant compounds in tomato and gives the characteristic red color to most tomato cultivars on the market. Lycopene and other bioactive compounds are responsible for the antioxidant activity of tomato, which prevents the oxidation of essential molecules caused by free radicals, and significantly contributes to the maintenance of human health, including the prevention of heart disease and prostate cancer (Porto et al., 2016). In addition to the beneficial effects of carotenoids against cancers, heart diseases, and macular degeneration, investigations on the role of these compounds as antioxidants and regulators of the response of the immune system were recognized (Uenojo et al., 2007).

The use of saline irrigation benefited the organoleptic characteristics and the Na concentration. Under salinity conditions, the fruits had better quality; however, these conditions were negatively correlated with the CFN, CFW, PH, YIELD, LCI, N, Ca, Mg, and S, which were harmful to tomato production and nutritional components. The toxic effects of salinity hinder plant development, reducing the gains of the traits evaluated when cultivated under severe salinity. The severe salinity affected tomato traits related to PH, the number of commercial and noncommercial fruits, and the CFW and NCFW. As Siddiky et al. (2015) reported, we had a significant reduction in the weight and yield of tomato fruits under moderate salinity level concerning the control treatment in most of the genotypes used. Many plant species show an increase in proline content as a direct response to salt stress, which contributes to the protein molecules and membrane stabilization associated with ROS elimination in the cell (Bhushan et al., 2016). The damages are directly linked to the period of exposure, the concentration of salt, the water potential of the cultivar, and the volume of water transpired by the plant (Negrão et al., 2017). Decreasing internal osmotic potential is generally reported as a strategy to maintain cell turgor, allowing growth through cell elongation under low external water potential (Yamaguchi & Blumwald, 2005). Plants subjected to salinity levels caused by NaCl could manage this osmotic restriction in the long term under field conditions. However, a physiological strategy verified in a tomato species to achieve this balance was the osmotic adjustment to maintain tissue hydration (Martínez et al., 2012).

Characterizing genetic divergence under salt stress conditions demonstrates the stability of genotypes in different environments. The groups formed under ideal conditions accurately show the relatedness of the genetic materials used. When subjected to abiotic stress, it was observed that the genotypes Sheena, Totalle, and Pizzadoro had high stability for forming a similarity group under conditions of moderate and severe salt stress. The Shanty, Ipa 6, and Maestrina genotypes had good stability and the greatest dissimilarity concerning the first group (Sheena, Totalle, and Pizzadoro), thus being the most promising in crossings to create plant populations with greater tolerance and stability under salt stress. The UPGMA clustering method, based on the generalized Gower distance, is the most consistent and indicated to characterize the genetic divergence among genotypes and provides greater precision when selecting cultivars for future crosses (Araújo et al. 2014). Also, the UPGMA clustering method demonstrated great precision under abiotic stress conditions in the wheat (*Triticum aestivum* L.) crop to select possible parents in plant-breeding programs (Oliveira et al., 2020).

This study brings valuable results for the protection of plants against salt stress, as it can provide benefits from the cultivation of tomato in regions with the presence of poor-quality water by adding commercial value to fruits produced with higher concentrations of carotenoids, flavonoids, soluble solids total, vitamin C, and total titratable acids that are beneficial to human health–also showing the genotypes with the best yields under salt stress conditions.

5 | CONCLUSIONS

Irrigation with saline water improves the organoleptic characteristics of tomato fruits by increasing the contents of carotenoids, flavonoids, vitamin C, total phenolic compounds, total soluble solids, and total titratable acids. However, it reduces the pollen grain fecundity, causing a decrease in the fruit yield and producing tomato fruits without seeds.

Shanty, Ipa 6, Maestrina, Sheena, Totalle, and Pizzadoro have the highest stability and dissimilarity under salt stress conditions. They can be considered promising parents in a breeding program aiming to obtain tomato genotypes salt stress tolerance.

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AUTHOR CONTRIBUTIONS

Carlos Eduardo da Silva Oliveira: Conceptualization, experiment conduction, writing, and reviewing. Tiago Zoz: Conceptualization, funding, supervision; statistical analysis, writing, and reviewing. Cassio de Castro Seron: Statistical analysis, writing, and reviewing. Eduardo Henrique Marcandalli Boleta: Organoleptic analysis, writing, and reviewing. Bruno Horschut de Lima: Organoleptic analysis, writing, and reviewing. Lucas Raoni Roel Souza: Organoleptic analysis; writing, and reviewing. Denise Renata Pedrinho: Organoleptic analysis; writing, and reviewing. Rosemary Matias: Organoleptic analysis; writing, and reviewing. Cinthia dos Santos Lopes: Writing and reviewing. Sebastião Soares de Oliveira Neto: Statistical analysis, writing, and editing. Marcelo Carvalho Minhoto Teixeira Filho: Funding, writing, and reviewing.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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