



Ameliorative effects of press mud and gypsum on soil quality, growth and physiology of guava (*Psidium guajava*) cultivar Hisar Safeda under RSC water irrigation

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ABSTRACT

Presence of Residual sodium carbonate (RSC) in irrigation water is a critical threat to agricultural sustainability as it deteriorates soil structure and fertility due to high sodium concentration. This experiment was conducted during 2021 to 2023 at ICAR-Central Soil Salinity Research Institute, Karnal, Haryana to evaluate the effects of sodic water irrigation with or without amendments (press mud and gypsum) on soil quality, growth, physiological and biochemical parameters of guava (*Psidium guajava* L.) cultivar Hisar Safeda. Ten different treatments including best available water (non-sodic water as control) and 3 RSC levels (2.5, 5.0 and 7.5 meq/L) with or without amendments were arranged in RBD with five replications. The results demonstrated that increasing RSC levels raised soil pH but reduced nitrogen and phosphorus availability, significantly impacting growth and physiological parameters. Growth and physiological traits declined with higher RSC, with the lowest values at 7.5 meq/L without amendments. Conversely, proline content and antioxidant enzyme activities increased under elevated sodicity, reflecting stress responses. Amendments improved growth, physiological and biochemical traits at all RSC levels, with gypsum outperforming press mud, likely by supplying essential nutrients and improving soil ionic balance. Results indicated that Hisar Safeda could be irrigated with sodic water up to RSC ~2.5 meq/L with amendments without any noticeable reduction in growth and physiological parameters, suggesting it as a viable sustainable practice for guava cultivation under sodic conditions. The present study also offers valuable insights for sustainable management of sodic water and soils using amendments like gypsum and press mud to maintain productivity and soil health.

Keywords: Growth parameters, Irrigation, Residual sodium carbonate, Sodic water, Soil quality

Groundwater is the primary source of supplementary irrigation in India. The availability of good quality water is becoming a limiting element in agricultural output throughout the globe (Hazra and Avishek 2010). The average percentage of groundwater in Haryana state for good quality, normal quality or poor quality is 37%, 8% and 55% (18% sodic, 11% saline and 26% saline-sodic water), respectively (Mandal 2024). Sodic water with Residual sodium carbonate (RSC) of more than 2.5 meq/L has been found unsuitable for irrigation (Minhas *et al.* 2019). Sodium carbonate and/or bicarbonate in RSC_{iw} poses soil hardness, restricted aeration and permeability (Minhas *et al.* 2019). Soil hardness leaves little room for air and water to circulate in plant roots and nutrient flows. Additionally, changes also occur in soil EC, pH, sodium absorption ratio (SAR), exchangeable sodium

percentage (ESP) (Choudhary *et al.* 2011a) and cations/anions ratio present in the soil solution and on exchange sites resulting in salt toxicity and nutrient deficiency (Sharma and Minhas 2005). Kaur and Choudhary (2008) reported that prolonged and irresponsible use of sodic waters alters soil organic carbon quality and microbial biomass count (MBC).

Gypsum, a calcium source, is used as an amendment for sodic soils. Earlier studies showed its role in solubilising calcium from native carbonates, reducing soil pH, ESP, SAR and improving infiltration and yield (Choudhary *et al.* 2011b, Minhas *et al.* 2019). Press mud, a sugar industry by-product, contains macro- and micro-nutrients with calcium sulphate. As an organic amendment, it supplies calcium, replaces sodium on the exchange complex, aids sulphur conversion to sulfuric acid and solubilises native carbonates, making it a potential substitute for sodic soil reclamation (Sheoran *et al.* 2020).

Guava (*Psidium guajava* L., 2n=22, x=11), a member of Myrtaceae, is called the poor man's apple for its high nutritive value and low cultivation cost (Kumar *et al.* 2016b, Kumar *et al.* 2017a). Hardy and highly productive

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under diverse conditions (Kumar *et al.* 2014, Sharma *et al.* 2010), it is valued globally for nutrition, calorific content, quality traits and low price, earning the title “Super fruit” in India. Integrating hardy crops with cost-effective amendments like gypsum or press mud helps sustain yield and mitigate alkalinity stress from residual sodium carbonate in irrigation water. Hence, this study was carried out to assess RSC_{iw} effect on soil, growth, physiological and biochemical parameters of guava cv. Hisar Safeda and evaluate amendment effectiveness.

MATERIALS AND METHODS

Experimental site: The present investigation was carried out during 2021 to 2023 at ICAR-Central Soil Salinity Research Institute, Karnal (29°42'N, 76°57'E; at an elevation of 250 m amsl), Haryana in lysimeters [100 kg capacity; 53 cm (height) × 40 cm (diameter)] having no drainage and filled with sandy loam soil. The climate of region is semi-arid and subtropical-monsoon type with annual rainfall of 1319.3 mm, 70–80% of which is received during July–September months (Table 1).

Planting material: One-year-old seedlings of Hisar Safeda plants were procured from Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana to ensure purity and quality. Healthy, disease-free plants were transplanted into lysimeters during the 2021 rainy season, filled with a homogeneous 3:1:1 mixture of garden soil, compost and sand (85 kg, bulk density 1.5 g/cm³). Irrigation was based on bulk density and evaporation, with standard CCSHAU practices and IPM measures were followed for

establishment. After six months, plants received either good-quality or sodic irrigation water, with treatments applied as per soil bulk density and porosity.

Treatment details: There were total of ten treatments, viz. T₁, Best Available Water (BAW) as control; T₂, RSC (Residual sodium carbonate)~2.5 meq/L; T₃, RSC ~2.5 meq/L + press mud; T₄, RSC~2.5 meq/L + gypsum; T₅, RSC~5 meq/L; T₆, RSC~5 meq/L + press mud; T₇, RSC~5 meq/L + gypsum; T₈, RSC~7.5 meq/L; T₉, RSC~7.5 meq/L + press mud; and T₁₀, RSC~7.5 meq/L + gypsum. The experiment was laid out in a randomised block design (RBD) with five replications for each treatment. The BAW was sourced from ICAR- Central Soil Salinity Research Institute, Karnal with pH 6.2, EC 0.2 dS/m and RSC nil (meq/L). Initial soil and water parameters are detailed in Table 2.

The underground sodic water was brought from village Mundri, district Kaithal and stored in a plastic container for subsequent irrigation based on the daily pan evaporation. The collected water samples were analysed for various chemical parameters, viz. EC_{iw}, pH_{iw}, cationic (Na⁺, Ca²⁺ and Mg²⁺) and anionic (CO₃²⁻, HCO₃⁻) composition following standard methods as given in Richards (1954) (Table 3). The residual sodium carbonate (RSC) was calculated using the given formula:

$$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$$

Gypsum and press mud were applied at the start of each season; gypsum was added with irrigation water while press mud was mixed into the soil. Gypsum amounts were 1.08 g, 3.78 g and 6.48 g for RSC ~2.5, ~5.0 and ~7.5 meq/L

Table 1 Meteorological data on temperature, relative humidity and rainfall during the course of investigation

Month	Average temperature (°C)		Relative humidity (%)		Total rainfall (mm)
	Maximum	Minimum	Morning	Evening	
July 2021	34.2	26.6	87.7	72.4	668.1
August 2021	33.0	26.4	92.4	76.9	146.1
September 2021	31.6	24.8	94.9	76.1	224.6
October 2021	31.5	19.0	88.9	49.5	85.6
November 2021	27.4	10.9	93.0	35.3	00.0
December 2021	21.2	07.6	97.2	62.5	01.2
January 2022	15.3	08.1	98	83	93.1
February 2022	21.1	08.1	97	56	29.9
March 2022	30.7	14.8	91	41	00.0
April 2022	39.6	19.6	54	15	00.0
May 2022	37.4	24.5	69	39	111.0
June 2022	38.4	25.6	70.2	42.4	52.8
July 2022	33.3	26.8	92.4	75.8	472.0
August 2022	33.1	26.1	92.9	75.5	108.4
September 2022	32.2	24.4	96.1	72.3	441.6
October 2022	31.0	18.4	93.6	50.2	18.0
November 2022	27.4	12.3	92.6	44.5	00.0
December 2022	20.8	07.9	97.1	62.1	01.2
January 2023	16.5	06.8	96	73	22.6

Table 2 Soil and water parameters at commencement of experiment

Soil parameter at commencement of experiment		Soil water saturation paste extract	
pH_2	7.21	Na^+ (meq/L)	3.79
EC_e (dS/m)	1.40	K^+ (meq/L)	0.59
Texture	Sandy loam	Ca^{2+} (meq/L)	5.2
Sand/silt/clay (%)	64.33/18.67/17.00	Mg^{2+} (meq/L)	4.4
Organic carbon (%)	1.1	SO_4^{2-} (meq/L)	7.50
Available nitrogen (N) kg/ha	227.52	Cl^- (meq/L)	6.50
Available phosphorus (P) kg/ha	64.5	CO_3^{2-} (meq/L)	Nil
		HCO_3^- (meq/L)	1.1

RSC, Residual sodium carbonate.

Table 3 Characterisation of RSC irrigation water (RSC_{iw})

Parameters	$RSC_{iw} \sim 2.5$ meq/L	$RSC_{iw} \sim 5$ meq/L	$RSC_{iw} \sim 7.5$ meq/L
pH	7.60 ± 0.21	7.56 ± 0.24	7.48 ± 0.30
EC (dS/m)	1.08 ± 0.08	1.12 ± 0.06	1.32 ± 0.10
Soluble salts (meq/L)			
$Ca^{2+} + Mg^{2+}$	0.52 ± 0.32	0.93 ± 0.40	3.55 ± 0.70
$CO_3^{2-} + HCO_3^-$	2.98 ± 0.31	6.10 ± 0.35	10.98 ± 0.78
Na^+	2.74 ± 0.12	6.10 ± 0.40	13.3 ± 0.40
Cl^-	1.88 ± 0.16	1.40 ± 0.12	0.90 ± 0.08
RSC (meq/L)	2.44 ± 0.12	5.13 ± 0.19	7.43 ± 0.24

RSC, Residual sodium carbonate. All cations and anions are in meq/L.

treatments, respectively, mixed in 9.04 L of water (based on soil weight and bulk density). Press mud quantities were 193.2 g, 386.4 g and 579.6 g, respectively for the same RSC levels. These rates were adjusted according to the RSC level of the irrigation water to achieve proportional amelioration of sodicity stress (Arora *et al.* 2018).

Data collection: Data of different parameters were taken during summer season (15th July 2022 to 15th August 2022) and winter season (15th December 2022 to 15th January 2023). Data of soil quality parameters (EC_2 , pH_2 , Soil organic carbon, available nitrogen and available phosphorus) were taken at the end of experiment. Growth parameters [plant height (% increase), spread E-W (% increase), spread N-S (% increase), stem girth (% increase), canopy volume (% increase), number of branches/plant, length of new emerging shoots and leaf area]; physiological and biochemical parameters [relative water content % (RWC), osmotic potential, membrane stability %, proline content and antioxidant enzymes (ascorbate peroxidase (APX), superoxide dismutase (SOD), peroxidase (POX) and catalase (CAT)) activity] were taken in both seasons (summer and winter).

Statistical analysis: Statistical analysis of data collected

during the study was done by using the complete randomised design and randomised block design as described by Panse and Sukhatme (1981). All the values are described as mean of the replicates with the evaluation of CD ($p=0.05$) level of significance by using software OPSTAT (Sheoran *et al.* 1998) and GRAPES (Gopinath *et al.* 2020).

RESULTS AND DISCUSSION

Soil quality parameters: Results obtained at the end of experiment revealed that RSC_{iw} with and without amendment had significant effect on soil pH_2 , available phosphorus and nitrogen in soil but had non-significant effect on soil EC_2 and soil organic carbon (Table 4). Soil pH_2 was lowest with BAW irrigation and increased with residual sodium carbonate (RSC) water, reaching its maximum at the highest RSC level (7.5 meq/L), followed by 5.0 and 2.5 meq/L, all exceeding the control treatment pH_2 . Singh *et al.* (2022) also reported increased soil pH_2 from sodic water irrigation. This rise is attributed to sodium bicarbonate and carbonate ions in sodic water, where sodium ions displace hydrogen ions in soil, reducing H^+ concentration and thus raising soil pH.

Application of press mud and gypsum to each level of RSC_{iw} reduced soil pH, with gypsum showing a more pronounced effect than press mud. Basak *et al.* (2021) and Dotaniya *et al.* (2023) similarly reported pH reduction under sodic water with these amendments. The decrease in pH may be explained by gypsum supplying Ca^{2+} to neutralise soluble HCO_3^- and displace Na^+ from soil's cation exchange complex. Similarly, decomposed press mud released low-molecular-weight organic acids (like acetic, citric, oxalic and humic acids) that released H^+ ions into soil solution which leads to reduction in soil pH.

Soil nitrogen availability was highest with best quality irrigation water and declined with increasing RSC, reaching a minimum at 7.5 meq/L RSC without amendment. Similar reduction under sodic water irrigation was reported by Liu *et al.* (2026). The decrease in available N was mainly due to elevated soil pH under sodic water, which promotes loss of NH_4^+ through volatilisation of NH_3 and reduces microbial activity responsible for N mineralisation. Application of amendments (press mud and gypsum) improved N availability at all RSC levels by alleviating the adverse effects of sodic water. This might be due to fact that application of amendments improves soil structure and microbial activity in soil and increased microbial activity helps in breakdown of organic matter to release nitrogen.

Phosphorus availability was highest with $RSC \sim 2.5$ meq/L (without amendment), followed by $RSC \sim 5.0$ meq/L and best quality water and was lowest at $RSC \sim 7.5$ meq/L. Singh *et al.* (2022) reported initial increases in P availability with sodic water, whereas Kumari *et al.* (2022) observed reductions at higher RSC. The decline at high RSC was likely due to higher soil pH causing P precipitation, reducing its solubility for plant uptake. Amendments (press mud and gypsum), however, decreased P availability across all RSC levels.

Table 4 Effect of different level of RSC_{iw} with and without amendments on soil quality parameters

Treatments			At the end of experiment				
			EC (dS/m)	pH	Soil organic carbon (%)	Available N (kg/ha)	Available P (kg/ha)
BAW (Control)		T ₁	0.41	7.27	0.98	215.68	70.83
RSC~2.5 meq/L	NA	T ₂	0.38	7.51	1.05	200.71	74.88
	Press mud	T ₃	0.41	7.42	1.10	214.23	73.27
	Gypsum	T ₄	0.46	7.36	1.00	212.13	69.87
RSC~5 meq/L	NA	T ₅	0.39	7.80	1.05	194.04	73.33
	Press mud	T ₆	0.57	7.65	1.10	210.88	62.07
	Gypsum	T ₇	0.67	7.29	0.97	211.32	62.50
RSC~7.5 meq/L	NA	T ₈	0.46	8.01	0.95	190.64	69.20
	Press mud	T ₉	0.41	7.79	1.01	208.87	56.50
	Gypsum	T ₁₀	0.41	7.68	0.97	207.44	55.33
CD (p=0.05)			NS	0.16	NS	9.26	10.89

NA denotes no amendment. RSC, Residual sodium carbonate.

Further, irrigation with different level of RSC water with and without amendment (press mud and gypsum) had no significant effect on soil EC₂ and soil organic carbon at the end of experiment. No significant effect on soil organic carbon was also reported by Kumar *et al.* (2017b).

Growth parameters: Growth parameters are vital in the cultivation of guava crop for several reasons, as they provide essential information about the health, development and productivity of the plants. Growth parameters like plant height (% increase), spread E-W (% increase), spread N-S (% increase), stem girth (% increase), canopy volume (% increase), number of branches/plant, length of new emerging shoots and leaf area were significantly decreased with different level of RSC of irrigation water and it was observed that highest level of RSC (7.5 meq/L) had most inhibitory effect on growth parameters followed by 5 meq/L and 2.5 meq/L. However, maximum value of growth parameters was noticed when guava cultivars were irrigated with best available water.

During summer, maximum increase in plant height (96.69%), spread E-W (87.84%), spread N-S (72.69%), stem girth (49.81%) and canopy volume (542.66%) were recorded under non-sodic water irrigation (T₁- control), which were statistically at par with T₂ (except canopy volume), T₃ (except canopy volume) and T₄. In winter, corresponding increases were 35.92%, 46.22%, 48.62%, 34.80% and 195.32%, respectively. Conversely, the lowest growth was observed under 7.5 meq/L RSC water without amendments (T₈), with increases of 71.21%, 53.80%, 43.17%, 29.59% and 280.67% in summer and 25.18%, 20.76%, 25.12%, 20.54% and 88.97% in winter, respectively. Maximum number of branches/plant (16.0 in summer, 28.6 in winter), shoot length (24.48 cm in summer, 17.58 cm in winter) and leaf area (53.32 cm² in summer, 48.07 cm² in winter) were also recorded with best available water (T₁). The minimum values (7.4 and 13.0 branches/plant, 12.78 and 11.16 cm shoot length and 37.60 and 32.28 cm² leaf

area in summer and winter, respectively) occurred under 7.5 meq/L RSC water without amendments (T₈) (Table 5).

Superior growth parameters with BAW and reduced growth with increasing RSC_{iw} were also reported by Machra *et al.* (2025), Singh *et al.* (2018) and Kumar *et al.* (2023). Declines in growth are mainly due to increased RSC in water, which precipitates calcium as CaCO₃, raises sodicity and worsens soil physical properties (compact and poorly aerated soils), leading to reduced soil permeability and root respiration, ultimately hindering plant growth. Additionally, salt accumulation causes water deficits and disturbs ion balance, interfering with necessary physiological functions and reducing vegetative growth. Elevated pH and ESP further restrict water supply to plants, explaining the reduction in growth parameters. While increasing RSC_{iw} negatively affected growth but addition of amendments (press mud and gypsum) improved growth at each RSC level, with gypsum having a more pronounced effect than press mud. Improvement in growth parameters due to application of amendments was also reported by Kumar *et al.* (2016a). The improvement is attributed to better soil properties, aeration, nutrient availability, root activity and water/nutrient absorption, supporting enhanced photosynthesis and assimilate production for growth. Moreover, replacement of Na⁺ by Ca²⁺ due to application of gypsum also pulls clay particles together much better due to more positive charges that leads to clay particles clumping into small groups or crumbs instead of floating apart. These crumbs increased more pores which is required for better water infiltration and soil aeration as well as drainage. These all conditions facilitate better plant growth.

Physiological and biochemical parameters of leaf: The experiment result revealed that maximum leaf RWC (88.89%), osmotic potential (-0.47 MPa) and membrane stability (78.59%) were observed in summer and 74.00%, -0.42 MPa and 75.78% in winter, respectively, under irrigation with best available water (T₁). The minimum

Table 5 Effect of different level of RSC_{iw} with and without amendments on growth parameters of guava cultivar Hisar Safeda

Treatments	PH		S _{EW}		S _{NS}		SG		CV		NBP		LNES		LA		
	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W	
BAW (Control)	T ₁	96.69 ^a	35.92 ^a	87.84 ^a	46.22 ^a	72.69 ^a	48.62 ^a	49.81 ^a	34.80 ^a	542.66 ^a	195.32 ^a	16.0 ^a	28.6 ^a	21.48 ^a	17.58 ^a	53.32 ^a	48.07 ^a
RSC~	T ₂	87.16 ^{abcd}	31.07 ^{abcd}	84.37 ^a	43.15 ^a	67.63 ^a	44.44 ^a	43.06 ^{ab}	29.13 ^{abcd}	487.04 ^{ab}	170.94 ^b	14.0 ^{cd}	25.2 ^b	20.28 ^b	16.46 ^b	48.80 ^c	43.61 ^c
2.5 meq/L	Press mud	T ₃	89.03 ^{abc}	31.73 ^{abc}	85.46 ^a	44.18 ^a	69.52 ^a	45.92 ^{ab}	31.13 ^{abc}	503.96 ^a	176.78 ^b	14.6 ^{bc}	26.2 ^b	20.70 ^{ab}	16.76 ^{ab}	49.61 ^c	44.26 ^c
	Gypsum	T ₄	92.14 ^{ab}	32.60 ^{ab}	87.24 ^a	45.75 ^a	70.50 ^a	46.74 ^{ab}	32.47 ^{ab}	525.12 ^a	182.84 ^{ab}	15.4 ^{ab}	27.6 ^a	21.00 ^{ab}	16.98 ^{ab}	51.44 ^b	45.88 ^b
RSC~	NA	T ₅	76.37 ^{cde}	27.02 ^{cde}	64.82 ^{bcd}	29.30 ^b	51.78 ^{bc}	31.68 ^b	23.59 ^{bcd}	344.21 ^c	116.08 ^c	10.6 ^f	19.2 ^c	16.38 ^d	14.04 ^d	41.48 ^f	36.98 ^f
5 meq/L	Press mud	T ₆	78.14 ^{cde}	28.20 ^{bcd}	68.23 ^{bc}	30.94 ^b	54.90 ^b	38.41 ^{bc}	24.67 ^{bcd}	366.57 ^c	122.83 ^c	12.0 ^e	22.2 ^d	17.18 ^{cd}	14.54 ^{cd}	43.57 ^e	38.77 ^e
	Gypsum	T ₇	80.02 ^{bcd}	28.73 ^{bcd}	69.22 ^b	31.76 ^b	55.94 ^b	33.77 ^b	25.21 ^{abcd}	375.82 ^{bc}	126.69 ^c	13.0 ^{de}	23.8 ^c	17.60 ^c	15.16 ^c	45.71 ^d	40.27 ^d
RSC~	NA	T ₈	71.21 ^e	25.18 ^e	53.80 ^d	20.76 ^c	43.17 ^c	29.59 ^c	20.54 ^d	280.67 ^c	88.97 ^d	7.4 ^g	13.0 ^g	12.78 ^e	11.16 ^f	37.60 ^h	32.28 ^h
7.5 meq/L	Press mud	T ₉	72.55 ^e	25.77 ^{de}	56.37 ^{cd}	21.84 ^c	45.38 ^{bc}	26.22 ^b	21.40 ^d	295.48 ^c	93.19 ^d	8.0 ^g	14.2 ^{fg}	13.44 ^e	11.76 ^{ef}	39.03 ^{gh}	33.46 ^{gh}
	Gypsum	T ₁₀	73.93 ^{de}	26.23 ^{de}	57.24 ^{bcd}	22.53 ^c	46.23 ^{bc}	26.78 ^b	21.98 ^{cd}	302.82 ^c	95.84 ^d	8.4 ^g	15.2 ^f	13.88 ^e	12.12 ^e	39.30 ^g	33.93 ^g
CD (p=0.05)			13.33	5.50	12.36	5.65	11.68	9.86	10.73	114.78	17.81	1.24	1.39	1.10	0.86	1.68	1.49

Means within a column followed by at least one common letter do not differ significantly according to Tukey's test ($p < 0.05$). BAW, Best available water; RSC, Residual sodium carbonate; PH, Plant height (% increase wrt to initial); S_{EW}, Canopy spread (east-west) % increase; S_{NS}, Canopy spread (north-south) % increase; SG, Stem girth; CV, Canopy volume; NBR, Number of branches/plant; LNES, Length of newly emerged shoots (cm); LA, Leaf area (cm²). S and W denote summer and winter seasons, respectively. NA denotes no amendment.

values, 65.07%, -1.35 MPa and 39.14% in summer and 55.18%, -1.26 MPa and 34.96% in winter, occurred under irrigation with RSC~7.5 meq/L without amendment (T₉) (Table 6).

The experiment (Table 6) showed minimum leaf proline content (338.69 µg/g DW), APX (0.95 units/g FW), SOD (21.41 units/g FW), POX (3.75 units/g FW) and CAT activity (5.15 units/g FW) in summer and 376.88 µg/g DW, 0.93, 19.77, 3.62 and 4.72 units/g FW, respectively in winter under best available water (T₁). Maximum values- proline (978.07 µg/g DW), APX (2.48 units/g FW), SOD (37.36 units/g FW), POX (6.21 units/g FW) and CAT (10.51 units/g FW) in summer and 1031.86 µg/g DW, 2.33, 33.69, 5.80 and 9.35 units/g FW, respectively in winter were recorded under RSC~7.5 meq/L without amendments (T₈).

Different levels of RSC_{iw}, with or without amendments, significantly affected above-mentioned physiological and biochemical leaf parameters of Hisar Safeda during both summer and winter seasons. Maximum RWC, osmotic potential and membrane stability were observed under irrigation with best available water, while increasing RSC levels (7.5>5.0>2.5 meq/L) caused progressive reductions. Similar reductions in RWC and osmotic potential (Kumar *et al.* 2023) and membrane stability (Aljuaid *et al.* 2022) have been reported. This is likely due to salt build-up (CO₃²⁻ and HCO₃⁻ of Na) causing clay mineral dispersion, poor soil aeration and permeability issues. Higher RSC also increased membrane injury index and sodium concentration, which plants could not tolerate as well as at lower RSC or best water. The addition of amendments mitigated negative effects at each RSC level by improving ionic balance in soil and plants, facilitating better physiological behaviour. Between them, gypsum showed a more promising effect than press mud, likely due to supplementation of essential mineral nutrients helping maintain soil and plant ionic balance.

Increasing RSC also raised proline content and antioxidant enzyme activities, with the highest values at 7.5 meq/L followed by 5.0 and 2.5 meq/L, while minimum values were under best available water. Similar increases have also been documented by Rajkumar *et al.* (2025). These biochemical responses, including accumulation of compatible solutes like proline and elevated antioxidant enzymes, are plant defences against abiotic stresses (Dhiman *et al.* 2026). Osmotic adjustment through increased proline accumulation is a key adaptive mechanism in plants under sodicity stress. High RSC_{iw} generates reactive oxygen species (ROS) which encourages the plant's defence mechanism that involves enhanced synthesis of enzymatic antioxidants. SOD serves as the first line of defense by converting superoxide anions (O₂⁻) into molecular oxygen (O₂) and hydrogen peroxide (H₂O₂). CAT subsequently decomposes H₂O₂ into water (H₂O) and O₂, thereby mitigating oxidative damage and maintaining cellular homeostasis (Chahal *et al.* 2023). Application of amendments reduced proline content and antioxidant enzyme activities across all RSC levels, with gypsum causing a greater decrease than press mud. This decline suggests amendments alleviated oxidative stress

Table 6 Effect of different level of RSC_{1w} with and without amendments on physiological and biochemical parameters of leaves of guava cv Hisar Safeda

Treatments	Physiological parameters of leaf										Biochemical parameters of leaf									
	RWC		OP		MS		Proline		APX		SOD		POX		CAT					
	S	W	S	W	S	W	S	W	S	W	S	W	S	W	S	W				
BAW (Control)	T ₁	88.89 ^a	74.00 ^a	-0.47 ^a	-0.42 ^a	78.59 ^a	75.78 ^a	338.69 ^g	376.88 ^f	0.93 ^g	21.41 ^g	19.77 ^g	3.75 ^c	3.62 ^h	5.15 ^f	4.72 ^f				
RSC~	T ₂	80.60 ^{cd}	68.22 ^{bcd}	-0.67 ^c	-0.61 ^b	63.38 ^c	60.00 ^c	507.45 ^e	564.17 ^e	1.42 ^c	27.20 ^e	24.84 ^e	4.91 ^c	4.57 ^f	7.20 ^e	6.30 ^e				
2.5 meq/L	T ₃	82.07 ^c	70.84 ^{abc}	-0.62 ^{bc}	-0.56 ^b	67.67 ^c	65.06 ^b	480.92 ^e	547.18 ^e	1.40 ^c	25.32 ^f	23.44 ^f	4.59 ^d	4.31 ^g	6.92 ^e	6.12 ^e				
Gypsum	T ₄	85.29 ^b	72.06 ^{ab}	-0.60 ^b	-0.55 ^b	68.11 ^b	65.49 ^b	425.54 ^f	520.10 ^e	1.41 ^c	26.44 ^{ef}	24.06 ^{ef}	4.56 ^d	4.30 ^g	6.94 ^e	6.00 ^e				
RSC~	T ₅	76.42 ^e	63.60 ^e	-1.01 ^e	-0.92 ^d	50.20 ^e	47.31 ^e	643.42 ^c	729.07 ^c	1.84 ^e	31.86 ^c	28.50 ^c	5.73 ^b	5.35 ^{cd}	8.49 ^c	7.49 ^c				
5 meq/L	T ₆	78.75 ^{de}	65.18 ^{de}	-0.89 ^d	-0.85 ^c	55.43 ^d	52.04 ^d	614.15 ^c	698.90 ^{cd}	1.62 ^d	30.08 ^d	27.21 ^d	5.52 ^b	5.08 ^c	8.03 ^d	7.12 ^d				
Gypsum	T ₇	80.54 ^{cd}	66.98 ^{cde}	-0.85 ^d	-0.81 ^c	58.98 ^d	56.59 ^c	556.88 ^d	663.67 ^d	1.57 ^d	30.05 ^d	26.92 ^d	5.57 ^b	5.15 ^{de}	7.81 ^d	6.86 ^d				
RSC~	T ₈	65.07 ^g	55.18 ^f	-1.35 ^h	-1.26 ^g	39.14 ^g	34.96 ^g	978.07 ^a	1031.86 ^a	2.48 ^a	37.36 ^a	33.69 ^a	6.21 ^a	5.80 ^a	10.51 ^a	9.35 ^a				
7.5 meq/L	T ₉	67.10 ^{fg}	57.24 ^f	-1.19 ^g	-1.15 ^f	45.61 ^f	41.22 ^f	910.18 ^b	980.04 ^b	2.31 ^b	34.26 ^b	31.24 ^b	6.15 ^a	5.69 ^{ab}	9.86 ^b	8.72 ^b				
Gypsum	T ₁₀	68.38 ^f	58.56 ^f	-1.10 ^f	-1.07 ^e	48.29 ^{ef}	43.57 ^f	870.47 ^b	961.83 ^b	2.27 ^b	34.48 ^b	31.51 ^b	6.06 ^a	5.57 ^{bc}	9.52 ^b	8.41 ^b				
CD (p=0.05)		3.10	4.23	0.058	0.055	3.80	3.60	42.99	47.32	0.08	1.38	1.25	0.25	0.23	0.37	0.33				

Means within a column followed by at least one common letter do not differ significantly according to Tukey's test ($p < 0.05$). BAW, Best available water; RSC, Residual sodium carbonate; RWC, Relative water (%) content; OP, Osmotic potential (Mpa); MS, Membrane stability (%); APX, Ascorbate peroxidase (units/g FW); SOD, Superoxide dismutase (units/g FW); POX, Peroxidase (units/g FW); CAT, Catalase (units/g FW). S and W denote summer and winter seasons, respectively. NA denotes no amendment.

by reducing ROS production, thus lowering the need for extensive antioxidant defence.

RSC~2.5 meq/L irrigation water has at par effect on plant morphological, physiological and biochemical parameters of guava cultivar Hisar Safeda; hence, it can be recommended for guava irrigation. Negative effect of RSC water could be decreased with application of amendment like gypsum and press mud. Gypsum is more promising in mitigating effects of RSC water in comparison to press mud in guava cultivation.

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