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Physiological and Biochemical Responses of Pearl Millet and Mustard to Cut-Soiler-Based Shallow Subsurface Drainage Under Saline Irrigation

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Abstract

Inadequate drainage and the application of salty irrigation waterinduced salinity stress, poses a major constraint to agricultural productivity, especially in saline–arid regions. Shallow subsurface drainage has emerged as a potential technique for salinity management; however, its implications for crop physiological and biochemical responses remain unclear. Therefore, a two-year lysimetric study was undertaken in a split-split plot design investigating cut-soiler-based preferential shallow subsurface drainage (PSSD), soil type (saline sandy loam and normal silty clay loam), and irrigation water salinity levels (4, 8 and 12 dS m^{-1}) to evaluate the effectiveness of rice-residue-filled cut-soiler PSSD in mitigating salinity stress in pearl millet and mustard crops. The cut-soiler PSSD reduced root-zone salinity to around 60.0% by the end of experimentation. Lower root-zone salinity under cut-soiler PSSD alleviated osmotic and ionic stress by reducing hydrogen peroxide (11.0–14.6%), membrane injury (22.7–40.8%), lipid peroxidation (20.0–25.0%), proline accumulation (26.0–37.0%) and improving the Na^+/K^+ ratio (44.0%). Antioxidant enzyme activities were also significantly moderated under the cut-soiler PSSD. These physiological and biochemical improvements resulted in significant increases in grain and seed yield of pearl millet (23.5%) and mustard (31.4%), respectively. The findings of this study indicate that cut-soiler PSSD is an effective strategy to mitigate salinity stress at the physiological and biochemical level and offers sustainable management strategies for salt-affected agro-ecosystems.

Keywords: cut-soiler; salinity; pearl millet; mustard; physiological and biochemical response

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1. Introduction

Soil salinity is one of the most prevalent constraints to agricultural productivity [1] and its effects are expected to increase under the changing climate scenario [2]. Among the abiotic stresses, soil salinity adversely affects 20% of cropland, which may increase up to 24–32% of the global land surface in the futuristic climate [3]. Around 90% of plant-based human food comes from about 30 crop plant species and most of them are salt-sensitive [4]. Though crops vary widely in their capacity to withstand salt [5], almost all significant glycophytic crops lower average yields by 50–80% in saline environments (EC 4–8 dS m^{-1}) [6]. High concentration of salts in the root zone imposes multiple constraints

on growth and functioning of plants. It increases the osmotic potential, leading to reduced water uptake, and therefore inhibits seed germination, growth, development and ultimately yield of crops [7]. Salinity also decreases chlorophyll and carotenoids, reduces stomatal conductance and impairs photosynthesis [8]. Excess sodium accumulation in plant tissues disrupts ion homeostasis, particularly by lowering the K^+/Na^+ ratio, essential for enzyme activity, membrane stability, and stomatal regulation [9]. Additionally, salinity also induces overproduction of reactive oxygen species (ROS), leading to oxidative stress, and increases hydrogen peroxide, membrane peroxidation and cellular damage [10]. In response to these changes, plants activate biochemical defense pathways like proline accumulation and increased antioxidative enzyme activity, but these adjustments often come at the cost of growth, photosynthetic efficiency and yield.

Pearl millet and mustard are dominant crops in arid and semi-arid regions and form an important cropping sequence in salt-affected soils [11] due to their moderate tolerance to salinity [12]. However, their physiological response to salinity mitigation through shallow subsurface drainage systems, such as cut-soiler preferential shallow subsurface drainage (PSSD), remains underexplored. As plant stress originates in the root-zone environment, its mitigation requires strategies that can modify the salinity distribution in the root zone. However, interventions may exhibit contrasting short- and long-term system response, with initial disturbance followed by functional recovery after the system stabilizes [13]. Conventional approaches such as mulching, deficit saline water irrigation and conjunctive use retard upward flux but often fail to substantially improve internal drainage or reduce salt concentration in the rhizosphere [14], and salts often reappear in the root zone.

Cut-soiler PSSD has emerged as a promising, sustainable and low-cost alternative [15]. The cut-soiler drains use rice residue as filling material, acting as preferential flow pathways to enhance the drainage function of soil and redistribution of salts [16]. Previous studies reported improvements in crop growth and yield under cut-soiler-based interventions but did not explore the underlying mechanisms for yield improvements. Studies have not explored the effect of salinity reduction upon cut-soiler intervention on osmotic, ionic and oxidative stress indicators in crops grown under saline irrigation. It was hypothesized that rice-residue-filled cut-soiler PSSD would lower root-zone salinity and thereby alleviate osmotic, ionic, and oxidative stresses in pearl millet and mustard, resulting in improved physiological performance and productivity under saline irrigation. Therefore, the present study was conducted to quantify the effect of cut-soiler PSSD on root-zone salinity reduction; assess osmotic, ionic and oxidative stress responses; and evaluate the impact of cut-soiler PSSD on growth and productivity of pearl millet and mustard under different soil textures and differential irrigation water salinity.

2. Materials and Methods

2.1. Experimental Setup

The experiment was conducted over two consecutive years (2019-21) in semi-controlled lysimeters at the ICAR Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana. Preferential shallow subsurface drainage (PSSD) was constructed manually in July, 2018, simulating the cut-soiler drains at a depth of 60 cm using rice residue (6 Mg ha^{-1}) as filling material. Each drainage channel measured approximately 2.0 m in length with a trapezoidal cross-section (15 cm top width, 10 cm bottom width and 10 cm height). One PSSD channel was constructed in the middle of the lysimeter and connected to a lateral outlet positioned at the same depth (60 cm) to facilitate the removal of salt-laden drainage water (Supplementary Figure S2). Nylon mesh and gravel filters were used at the drain outlet interface to prevent clogging. This configuration was adopted to create continuous preferential flow pathways for enhanced salt removal while maintaining structural stability

of the channels, as demonstrated in earlier studies on cut-soiler-based preferential shallow subsurface drainage systems [16,17].

2.2. Treatment Details

The experiment was laid out in lysimeters ($2 \times 2 \times 3$ m^3) in a split-split plot design with two replicates. It comprised 12 treatment combinations, two main-plot treatments (cut-soiler and without cut-soiler PSSD), two soil types as sub-plots (saline sandy loam and normal silty clay loam) and three irrigation water salinity levels (4, 8 and 12 dS m^{-1}) as sub-sub plots. The three irrigation water salinity levels were imposed by diluting natural saline water (ECiw 16 dS m^{-1}) collected from the Nain Experimental Farm, Panipat, Haryana. The ionic compositions of the irrigation water of different salinity are provided in Supplementary Table S1. Pearl millet (HHB-197) and mustard (CS-58) were grown in the *kharif* and *rabi* seasons, respectively, using standard agronomic practices.

2.3. Observations Recorded

2.3.1. Biochemical Traits

The assessment of membrane injury (MI) was done by the procedure of Dionisio-Sese and Tobita [18] and expressed in %. The concentration of malondialdehyde (MDA) was estimated using the procedure outlined by Loreto and Velikova [19]. Proline content (mg g^{-1} fresh weight) was estimated using 3% sulphosalicylic acid [20]. H_2O_2 content was estimated following the method outlined by Sinha [21].

2.3.2. Antioxidant Enzyme Activities

Leaf samples were collected from the top visible dewlap leaf in pearl millet and from the uppermost fully expanded, physiologically active leaf in mustard. Fresh leaf tissue (300 mg) was homogenized in 2 mL of 0.1 M potassium phosphate buffer (pH ~7.0) and centrifuged at 10,000× *g* for 15 min. The resultant supernatant was extracted for enzyme activity tests. Superoxide dismutase (SOD, EC1.15.1.1) activity was determined following the method of Beauchamp and Fridovich [22] based on its ability to prevent the photochemical reduction of nitroblue tetrazolium (NBT). Catalase (CAT, EC1.11.1.6) activity was determined following the procedure described by Aebi [23]. The activity was assessed based on the reduction in absorbance at 240 nm, with values reported as U min^{-1} mg^{-1} protein. Ascorbate peroxidase (APX, EC1.11.1.11) activity was estimated based on the decline in absorbance at 290 nm according to Nakano and Asada [24], with results expressed as U min^{-1} mg^{-1} protein. Peroxidase (POX, EC1.11.1.7) is determined by measuring the rate of guaiacol oxidation at 470 nm in the presence of H_2O_2 [25].

2.3.3. Yield

Grain yield was recorded at harvest stage in both the crops.

2.3.4. Physiological Traits

Relative water content (RWC) is a useful indicator that compares the water content at a certain moment in percentage terms to the water content at full turgor [26]. Water potential (-MPa) was measured using chilled mirror dew point technique [27] on a WP4C Dewpoint potentiometer (METER Group, Inc., Pullman, WA, USA). Osmolality (mmol kg^{-1}) was recorded using 5 µL sap of leaves displayed on a digital meter of a Vapor Pressure Osmometer (Model 5600, ELITech Group, Zottegem, Belgium) and converted into osmotic potential (ψs) using the Van't Hoff equation in MPa [28]. Turgor potential was obtained by deducting the total water potential and the osmotic potential. Total chlorophyll was quantified according to Hiscox and Israelstam [29] and absorbance was measured at wavelengths of 663, 645, and 440.5 nm to quantify photosynthetic pigments. Gas exchange

attributes, i.e., stomatal conductance, transpiration and photosynthetic rate, were measured using the portable photosynthetic system (Li 6800, Li-Cor Biosciences, Lincoln, NE, USA) between 10 AM and 12 PM. Leaf area (cm^2) was taken using a Portable Laser leaf area meter (Model CI-202, CID Bio Science, Inc., Camas, WA, USA). Chlorophyll fluorescence (Fv/Fm) was determined using a portable pulse modulated fluorescence measurer (Junior PAM Chlorophyll Fluorometer, Effeltrich, Germany) after adapting the leaves to the dark for 5 min via special leaf clips. For estimation of Na^+ and K^+, fresh leaf samples collected at reproductive stage were washed with distilled water, oven-dried at 70 °C to a constant weight, and finely ground. A 100 mg dried sample was digested in 10 mL of a di-acid mixture of HNO_3:$HClO_4$ (3:1 *v*/*v* ratio). Sodium (Na^+) and potassium (K^+) concentrations were determined using NaCl and KCl as standards on a flame photometer (Systronics India Ltd., Ahmedabad, India). The Na^+/K^+ ratio was calculated on a concentration basis.

2.4. Statistical Analysis

The data were subjected to statistical analysis by analysis of variance (ANOVA) for split-split plot using SAS 9.2 software (SAS Institute, 2001) and Indian NARS Statistical Computing Portal http://sscnars.icar.gov.in/spltfactm2s2.aspx (accessed on 14 June 2021). Pair-wise comparison of the treatments' effect were made using Tukey's test at $p \leq 0.05$.

3. Results

3.1. Reclamation of Salinity

Soil salinity decreased substantially in all the treatments after two years of experimentation (Figure 1 and Supplementary Figure S1). The reductions were significantly higher under the cut-soiler (CS) treatment than without cut-soiler (WCS) treatment in both the soil types. In saline sandy loam soil, the initial salinity of 6.7 dS m^{-1} decreased to 5.2 dS m^{-1} (23.0%) in WCS and 2.8 dS m^{-1} (58.4%) in the CS treatment. The corresponding values of reduction for the normal clay loam soil were 3.0 dS m^{-1}(14.6%) and 1.26 dS m^{-1} (64.0%) from an initial salinity of 3.5 dS m^{-1}.

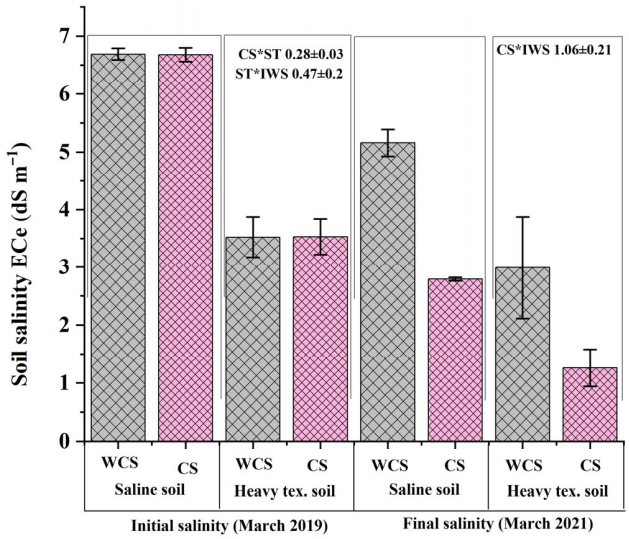


Figure 1. Cut-soiler PSSD mediated reclamation of salinity in saline and heavy-textured soils.

3.2. Biochemical Traits

Hydrogen peroxide (H_2O_2) content in leaves of both pearl millet and mustard was significantly affected by the cut-soiler treatment, soil type and irrigation water salinity (Figures 2A and 3A). Across both the crops, H_2O_2 concentration increased with increasing ECiw from 4 to 12 dS m^{-1} and was consistently higher in saline than heavy-textured

soil. The CS intervention significantly reduced the H_2O_2 accumulation in both the crops compared to the WCS. In pearl millet grown on saline soil, CS reduced H_2O_2 content by 9.2%, 11.0% and 11.8% when irrigated with ECiw of 4, 8 and 12 dS m^{-1}, respectively, whereas the corresponding values of reduction in mustard were 14.4%, 16.0% and 19.3%. In heavy-textured soil, the CS lowered H_2O_2 content by 8.8 to 12.5% in pearl millet while a comparatively greater reduction was observed in mustard (11.2–13.6%).

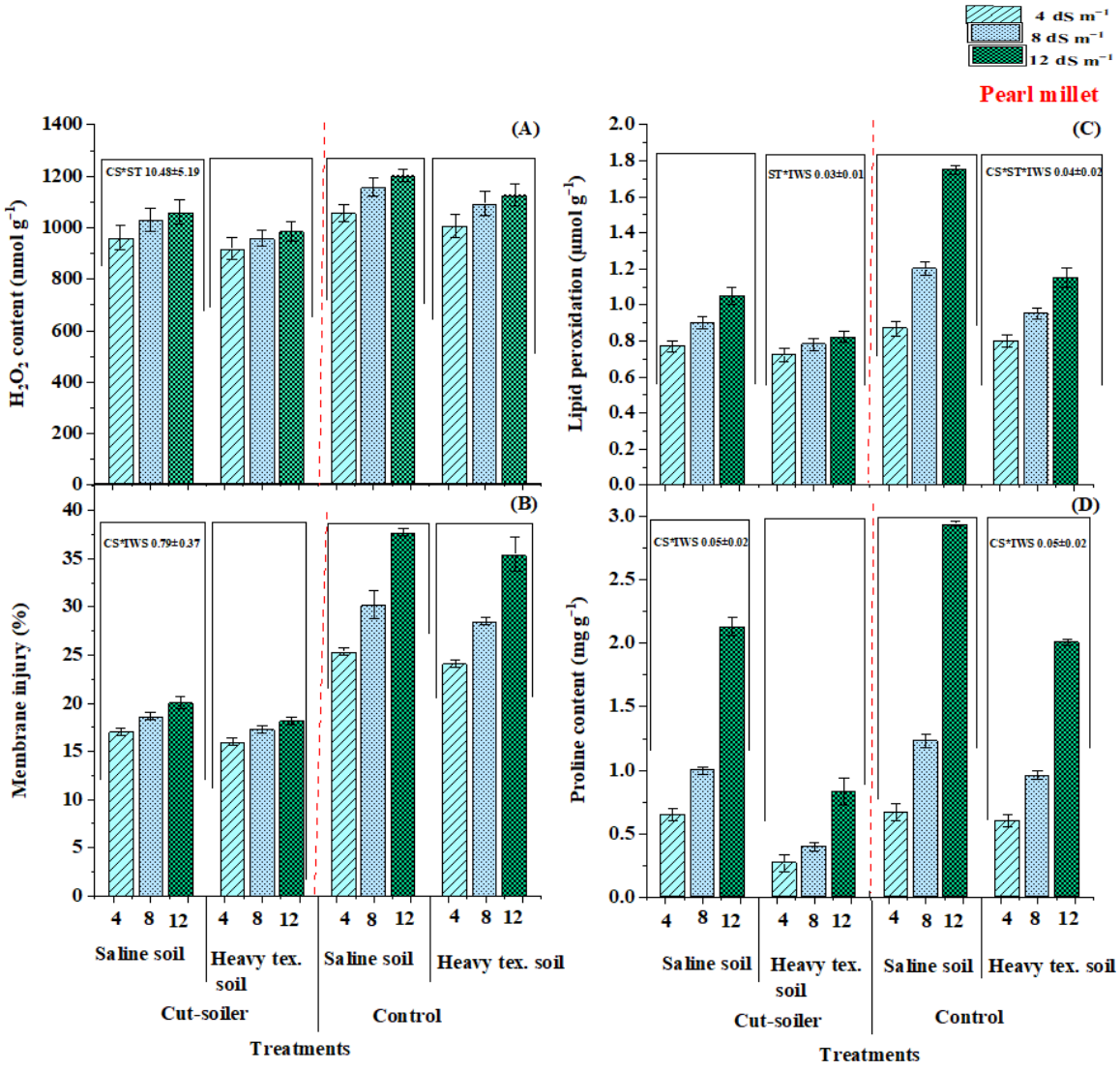


Figure 2. Effects of cut-soiler, soil type and irrigation water salinity on H_2O_2 content (**A**), membrane injury (**B**), lipid peroxidation (**C**) and proline content (**D**) in pearl millet.

Consistent with the observed changes in H_2O_2 content, membrane injury (MI) and malondialdehyde (MDA) levels also increased progressively with increasing irrigation water salinity in both pearl millet and mustard across different soil types (Figures 2B,C and 3B,C). Under WCS, MI in pearl millet ranged from 25.4 to 37.7% in saline soil and from 24.1 to 35.5% in heavy-textured soil across different ECiw levels; however, upon the intervention of CS, it reduced by 33.8–48.7% in saline soil and 24.1–35.5% in normal heavy-textured soil. Likewise, MDA content was significantly higher under WCS and declined by 11.5–40.0% under CS across soils. A similar response was observed in mustard, although the magnitude of change differed between soil types. Under WCS, mustard exhibited higher MI and MDA values in saline soil than in heavy-textured soil. Cut-soiler application reduced MI by 20.0–25.0% and MDA content by 17.0–23.0% across ECiw levels compared to WCS.

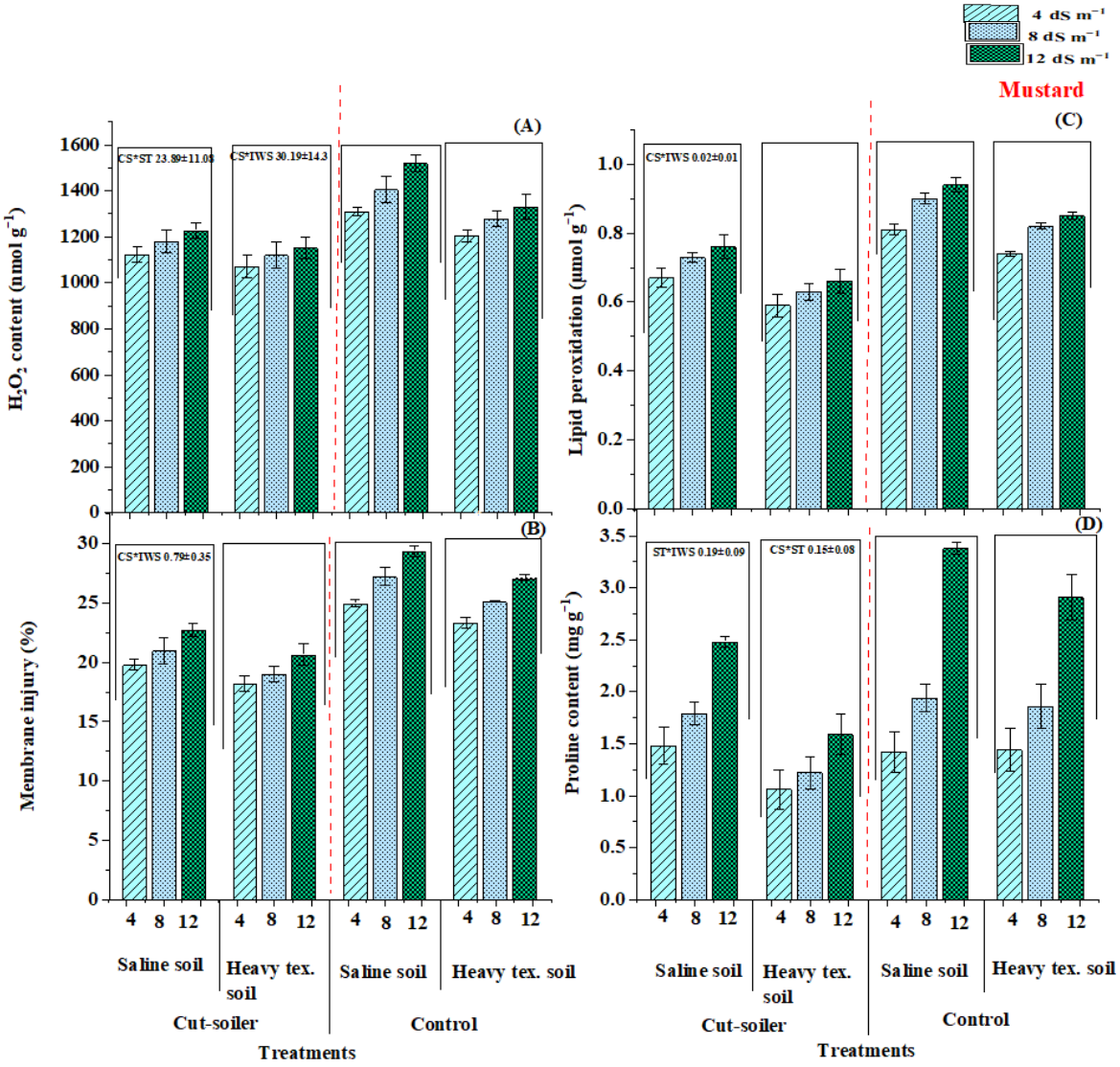


Figure 3. Effects of cut-soiler, soil type and irrigation water salinity on H_2O_2 content (**A**), membrane injury (**B**), lipid peroxidation (**C**) and proline content (**D**) in mustard.

Proline acts as an osmo-regulator and ROS-scavenging molecule. Its accumulation in leaves of both the crops increased significantly with increasing irrigation water salinity and was consistently higher under WCS than CS treatments (Figures 2D and 3D). In pearl millet, maximum proline accumulation was recorded under saline soil irrigated with 12 dS m^{-1} under WCS conditions. In mustard, proline content ranged from 1.4 to 3.4 mg g^{-1} in saline soil and from 1.5 to 2.5 mg g^{-1} in heavy-textured soil under WCS. Application of CS lowered proline content to 1.4–2.5 mg g^{-1} in saline soil and to 1.1–1.6 mg g^{-1} in heavy-textured soil across different ECiw levels.

3.3. Anti-Oxidative Enzyme Activities

Activities of antioxidant enzymes, *viz.*, catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX) and superoxide dismutase (SOD), as well as the Na^+/K^+ ratio, were significantly influenced by the cut-soiler, soil type and irrigation water salinity in both pearl millet and mustard (Table 1). Across both the crops, those without cut-soiler (WCS) treatment recorded significantly higher activities of CAT, POD, APX and SOD compared with cut-soiler treatment (CS). In pearl millet, CAT, POD, APX and SOD activities under WCS were 10.7, 9.0, 6.0 and 29.9 units g^{-1}, respectively, compared with 8.8, 5.7, 2.9 and

29.9 units g^{-1} under CS. A similar trend was observed in mustard, where WCS resulted in higher enzyme activities (CAT: 16.3; POD: 7.7; APX: 3.6; SOD: 58.6 units g^{-1}) than CS (13.2, 5.4, 2.5 and 51.9 units g^{-1}, respectively).

Table 1. Effects of cut-soiler, soil type and irrigation water salinity on anti-oxidative enzyme activities and Na^+/K^+ in pearl millet and mustard. Means followed by different letters differ significantly at $p = 0.05$.

	Pearl Millet					Mustard				
Treatments/ Traits	Catalase (Units/g)	Peroxidase (Units/g)	Ascorbate peroxidase (Units/g)	Superoxide dismutase (Units/g)	Na^+/K^+	Catalase (Units/g)	Peroxidase (Units/g)	Ascorbate peroxidase (Units/g)	Superoxide dismutase (Units/g)	Na^+/K^+
Cut-soiler										
Cut-soiler	8.75 ^{B}	5.76 ^{B}	2.92 ^{B}	25.83 ^{B}	0.25 ^{B}	13.16 ^{B}	5.39 ^{B}	2.53 ^{B}	51.90 ^{B}	0.30 ^{B}
Without Cut-soiler	10.76 ^{A}	8.98 ^{A}	5.97 ^{A}	29.92 ^{A}	0.45 ^{A}	16.27 ^{A}	7.70 ^{A}	3.57 ^{A}	58.60 ^{A}	0.53 ^{A}
CD (p = 0.05)	0.04 ± 0.02	0.13 ± 0.05	0.08 ± 0.03	0.09 ± 0.04	0.01	0.33 ± 0.14	0.14 ± 0.06	0.07 ± 0.03	0.71 ± 0.29	0.11 ± 0.03
Soil type										
Saline soil	10.32 ^{A}	8.43 ^{A}	4.89 ^{A}	29.34 ^{A}	0.42 ^{A}	15.27 ^{A}	7.88 ^{A}	3.39 ^{A}	57.31 ^{A}	0.50 ^{A}
Heavy textured soil	9.19 ^{B}	6.32 ^{B}	4.00 ^{B}	26.40 ^{B}	0.27 ^{B}	14.16 ^{B}	5.21 ^{B}	2.71 ^{B}	53.20 ^{B}	0.34 ^{B}
CD (p = 0.05)	0.05 ± 0.03	0.08 ± 0.04	0.07 ± 0.03	0.1 ± 0.05	0.01	0.2 ± 0.1	0.11 ± 0.05	0.06 ± 0.03	0.25 ± 0.13	0.06 ± 0.03
Irrigation water salinity										
S_1 (4 dS m^{-1})	9.29 ^{C}	6.74 ^{C}	4.04 ^{C}	27.18 ^{C}	0.32 ^{C}	13.91 ^{C}	5.96 ^{C}	2.85 ^{C}	53.82 ^{C}	0.37 ^{B}
S_2 (8 dS m^{-1})	9.83 ^{B}	7.50 ^{B}	4.51 ^{B}	27.90 ^{B}	0.34 ^{B}	14.80 ^{B}	6.61 ^{B}	3.08 ^{B}	55.53 ^{B}	0.40 ^{B}
S_3 (12 dS m^{-1})	10.13 ^{A}	7.88 ^{A}	4.78 ^{A}	28.54 ^{A}	0.38 ^{A}	15.42 ^{A}	7.06 ^{A}	3.21 ^{A}	56.40 ^{A}	0.48 ^{A}
CD (p = 0.05)	0.06 ± 0.03	0.1 ± 0.05	0.08 ± 0.04	0.13 ± 0.06	0.01	0.25 ± 0.12	0.14 ± 0.07	0.08 ± 0.04	0.31 ± 0.15	0.07 ± 0.04

Soil type exerted a significant effect on antioxidant enzyme activities. Saline sandy loam soil consistently exhibited higher CAT, POD, APX, and SOD activities than normal silty clay loam soil in both the crops. Pearl millet grown on heavy-textured soil recorded a CAT activity of 9.1 unit g^{-1} which increased to 10.3 units g^{-1} under saline soil. The corresponding increases in POD, APX and SOD activity were 6.3 to 8.4, 4.0 to 4.9 and 26.4 to 29.3 units g^{-1}, respectively. A similar response was evident in mustard, with saline soil recording significantly higher enzyme activity than heavy-textured soil. Antioxidant enzyme activities increased with increasing irrigation water salinity in both pearl millet and mustard, attaining the highest values at ECiw of 12 dS m^{-1}.

Na^+/K^+ was also significantly affected by all the treatments and followed similar trends to antioxidant enzymes (Table 1). Across both the crops, WCS and saline soil recorded significantly higher Na^+/K^+ than CS and heavy-textured soil, respectively. Increasing irrigation water salinity led to a significant rise in the Na^+/K^+, with maximum values observed at ECiw 12 dS m^{-1} in both pearl millet and mustard.

3.4. Grain/Seed Yield

The grain yield of pearl millet was significantly affected by cut-soiler, soil types and irrigation water salinity (Figure 4). The cut-soiler treatment significantly increased the grain yield of pearl millet by 23.6%, i.e., 4.0 t ha^{-1}, in comparison to WCS (3.3 t ha^{-1}). The average yield under heavy-textured soil was 32.4% higher (4.2 t ha^{-1}) than the saline soil (3.2 t ha^{-1}). The effect of application of saline irrigation water was also found significant, where the pearl millet yield declined from 4.1 to 3.8 t ha^{-1} and then further to 3.2 t ha^{-1} with 4, 8 and 12 dS m^{-1} of applied irrigation water salinity, respectively. The interaction effect among all three treatments, i.e., cut-soiler, soil type and irrigation water salinity, was also found significant. The highest pearl millet grain yield (4.8 t ha^{-1}) was obtained under cut-soiler, heavy-textured soil with application of 4 dS m^{-1} salinity irrigation water and reduced with increments in soil and irrigation water salinity. The lowest yield (2.2 t ha^{-1})

was recorded in those without cut-soiler in saline soil, with application of 12 dS m^{-1} salinity irrigation water.

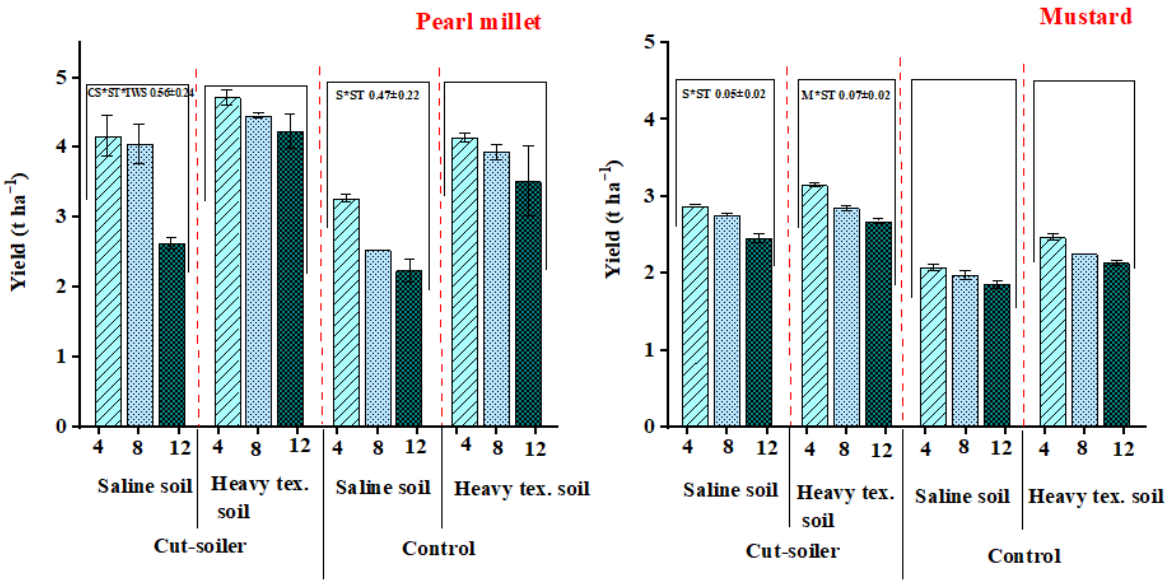


Figure 4. Effects of cut-soiler, soil type and irrigation water salinity on grain yield of pearl millet and mustard.

The cut-soiler treatment significantly increased the mustard seed yield (2.8 t ha^{-1}) compared to without cut-soiler (2.1 t ha^{-1}), representing a 31.5% increase. The average seed yield under heavy-textured soil was significantly higher (2.6 t ha^{-1}) than saline soil (2.3 t ha^{-1}). The effect of saline irrigation water treatments was also found significant. The mustard yield declined from 2.65 to 2.46 t ha^{-1} (7.2%) and then further to 2.3 t ha^{-1} (13.6%) with increasing salinity of applied irrigation water from 4 to 8 and 12 dS m^{-1}, respectively (Figure 4). The interaction effect of cut-soiler and irrigation water salinity also reached significance regarding seed yield of mustard. Seed yield was highest (3.2 t ha^{-1}) in heavy-textured soil with cut-soiler and irrigation water salinity level of 4 dS m^{-1}, and the lowest yield (1.9 t ha^{-1}) was observed in saline soil without cut-soiler and 12 dS m^{-1} salinity level of irrigation water. Similarly, the interaction effect of cut-soiler and soil type on seed yield of mustard was also found significant.

3.5. Change (%) in Studied Traits Under Cut-Soiler PSSD

Overall, significant positive results of cut-soiler PSSD were noted for the studied traits as well as in reclamation of salinity in both the crops. Figure 5 depicts the percent change in studied parameters under cut-soiler PSSD over without cut-soiler, featuring 6.6% and 6.5% increases in plant height, 19.9% and 48.0% increases in the number of tillers/branches per plant, 23.5% and 31.4% increases in grain yield, and 8.2% and 14.4% increases in straw/stover yield of pearl millet and mustard crops, respectively. The advantage of cut-soiler was also seen for physiological traits, with improvements of 4.2% and 11.5% in relative water content, reduced water potential by 19.3% and 18.3%, reduced osmotic potential by 19.6% and 15.7%, and reduced turgor potential by 10.5% and 9.7% in pearl millet and mustard, respectively. Gas exchange traits, i.e., photosynthetic rate enhanced by 9.3% and 28.0% in pearl millet and mustard, respectively, under cut-soiler technique. The chlorophyll content and leaf area increased by 23.0% and 23.5% in pearl millet and 22.8% and 13.6% in mustard, respectively. Stomatal conductance (gS), transpiration rate (E) and chlorophyll fluorescence also increased in a similar way under cut-soiler PSSD application. Membrane injury reduced by 40.8% and 22.7%, lipid peroxidation by 25.0% and 20.0%,

proline content by 37.0% and 26.0%, anti-oxidative enzymes by 18.0–35.0%, H_2O_2 content by 11.0% and 14.6%, and Na^+/K^+ by 44.0% in pearl-millet and mustard crops, respectively (Figure 5).

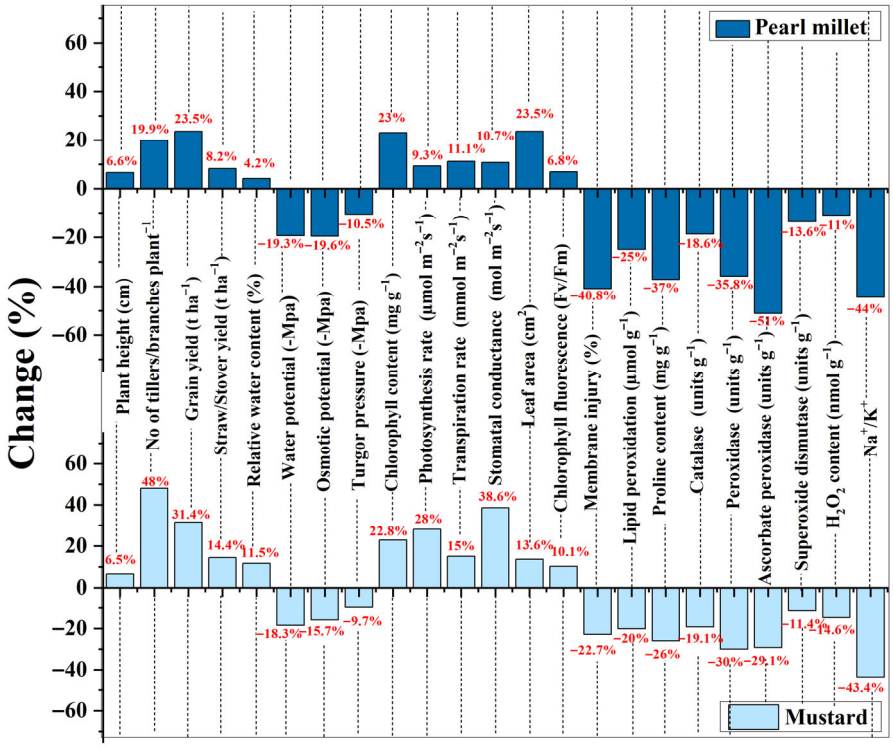


Figure 5. Percent change in different parameters of pearl millet and mustard crops under cut-soiler PSSD compared to without cut-soiler under salt stress.

4. Discussion

Cut-soiler-based residue filled shallow subsurface drainage has been identified as a promising technique to enhance the productivity of crops by mitigating salt stress [15,30]. The substantial decrease in soil electrical conductivity observed under cut-soiler treatment across both the soil types (Figure 1) demonstrates the effectiveness of rice-residue-filled preferential shallow subsurface drainage in salt removal from the root zone and is in confirmation with the earlier studies [15,30,31]. The cut-soiler PSSD facilitates movement of soluble salts by continuous preferential outflow [16]. The efficiency of preferential flow and solute transport of soils is governed by the moisture retention and release characteristics and hydraulic conductivity [32], which explains the greater magnitude of absolute salinity reduction in saline sandy loam soils as compared to normal silty clay loam soil. Similar texture-dependent hydrological behavior of soils has been reported in arid-region maize systems, where coarse-textured soils showed higher percolation fluxes and required frequent irrigations, while finer-textured soils showed greater water retention and slower subsurface fluxes [33]. Coarse-textured soils exhibit better connectivity of macropores [34], therefore allowing more rapid salt displacement through shallow subsurface drains, whereas heavy-textured soils respond more gradually. However, the significant salinity reduction recorded in both soil types reinforces the effectiveness of cut-soiler PSSD across different soil physical environments.

Salinity-induced osmotic and ionic stresses are direct consequences of high salt concentrations in the root zone and constitute the primary factors for subsequent physiological processes in crops [35]. Salinity alters the ionic concentration of soil solution with an increase in concentrations of Na^+ [36] and Cl^- ions [37,38], which leads to increased uptake

of these ions and a significant decrease in others [36,39,40]. In the present study, increasing irrigation water salinity intensified osmotic and ionic imbalance in both pearl millet and mustard. These were reflected as reduced plant water status and high Na^+/K^+. The responses obtained are consistent with the well-established effects of salinity on reducing water uptake and increasing sodium accumulation in plant tissues [41]. The cut-soiler intervention significantly moderated these stress responses across soil types and irrigation salinity levels. The consistently lower Na^+/K^+ observed under cut-soiler treatment indicates ionic regulation, which may have arisen from enhanced draining out of salts (sodium) from the rhizosphere. Saddiq et al. [42] also reported accumulation of high K^+ and low Na^+ in leaves of tolerant genotypes of wheat.

Maintenance of a lower Na^+/K^+ ratio is critical for sustaining enzyme activity, membrane stability and stomatal regulation. Munns and Tester [43] reported that the high accumulation of Na^+ in the leaf negatively affects the photosynthetic mechanism, resulting in a lower intake of carbohydrates to the young leaf, reducing root and shoot growth. The modification of Na^+/K^+ may serve as one of the mechanisms through which improved drainage under cut-soiler treatment may improve crop yields.

Osmotic stress and ion toxicity can also cause oxidative stress and a series of secondary stresses [44], as well as generating excess ROS that cause cytoplasmic membrane damage and irreversible metabolic dysfunction [45]. The production of ROS, *viz.*, O_2^-, H_2O_2, and OH^-, etc., is a stress indicator at the cellular level [46]. The increase in H_2O_2 content, membrane injury and lipid peroxidation with increasing irrigation water salinity in both the crops and soil types may be due to the increased oxidative burden, which led to increased ROS production [47]. However, the values were significantly lower under the CS treatment, which may be attributed to the reduced root-zone salinity. The improved ionic balance may have reduced ROS generation. The oxidative stress responses were further modulated by differences in soil texture. Saline sandy loam soils exhibited significantly higher oxidative stress indicators than normal silty clay loam soil, which was consistent with greater salt accumulation and osmotic stress intensity.

Proline accumulation significantly increased with increasing irrigation water salinity in both the crops. The increase was more pronounced under WCS. A similar increase in proline contents of pearl millet [48] and mustard cultivars was recorded upon salt exposure [49]. Proline is widely recognized as an osmo-protectant and ROS scavenger. The consistently lower proline content observed under CS across different crops may be attributed to the reduced osmotic and oxidative stress due to improved drainage.

Salinity-induced oxidative stress signals activation of antioxidant enzymatic defense systems as a protective response against the accumulation of ROS [43,45]. The increase in activities of key antioxidant enzymes (CAT, POD, APX, SOD) with increasing salinity of irrigation water in both the crops may be attributed to the increased oxidative pressure under saline conditions [50]. The higher enzyme activities under WCS likely indicate sustained ROS generation in response to persistent osmotic and ionic stress. An increase in the activity of these enzymes has also been reported in wheat under abiotic stresses [51]. Kiani et al. [45] also discovered that the CAT and POD activities of a barley mutant increased under salt stress with a concomitant reduction in levels of hydrogen peroxide and malondialdehyde in comparison to the wild type. The application of cut-soiler PSSD significantly lowered the activities of these enzymes. This moderated enzymatic response may be attributed to the reduced requirement for ROS scavenging due to alleviation of stress in the root zone. Improved drainage and reduced rhizospheric salinity under CS likely limited ROS production, thereby decreasing the need for antioxidant enzymes. Saline sandy loam soil exhibited significantly higher CAT, POD, APX and SOD activities than

normal silty clay loam soil in both the crops. This response corresponds with greater salinity-induced stress intensity in saline soil, which may require stronger biochemical defense.

Crop productivity under saline environments is ultimately determined by the extent to which plants can sustain physiological functioning. In the present study, the cumulative alleviation of osmotic, ionic and oxidative stress under cut-soiler PSSD was reflected as significant improvements in growth and yield of both pearl millet and mustard across soil types and irrigation water salinity levels. The reduction in salinity may have facilitated the use of energy for growth and development, which was previously being utilized in stress mitigation due to salinity [4]. Crop yields were improved by better drainage in cut-soiler plots, with 23.5% and 31.4% increases in grain yield and 8.2% and 14.4% increases in stover/straw yield of pearl millet and mustard crops, respectively. Multiple regression analysis revealed distinct, crop-specific stress-response associations (Supplementary Table S4). In pearl millet, yield variation was primarily explained by membrane injury and proline accumulation, which is consistent with the earlier findings of proline-mediated osmotic adjustment for salinity tolerance in millets [52]. In mustard, membrane injury, SOD and H_2O_2 were found to be significant predictors of yield. The findings reinforce that salinity-induced ROS accumulation and antioxidant enzyme modulation are central features of *Brassica* stress physiology [53,54]. Feng et al. [32] evaluated the durability of the impacts of saline water irrigation under subsurface drainage circumstances and revealed a smaller drop in summer maize production and concluded that subsurface drainage practices do offer crucial assistance for the long-term sustainable use of salt water for irrigation. In another study on cotton, shallow subsurface drainage was effective in reducing soil salinity and improving crop yields [31]. Accordingly, findings from earlier research [16,55] concluded that improved drainage function of soils reduced soil salinity and increased crop yields. However, the amount of monsoon rains received and the effectiveness of subsurface drainage determine the level of salt removal and crop establishment [56]. The cut-soiler PSSD produced a larger discharge of free water and salts with drainage and resulted in around 60% reduction in soil salinity after two years, which might have helped in enhancing the growth, physiology and production of pearl millet and mustard crops.

5. Conclusions

The cut-soiler intervention significantly reduced soil salinity, resulting in sustained physiological functioning of both pearl millet and mustard. The mitigation of salinity stress was reflected through coordinated reductions in osmotic, ionic and oxidative stress markers. The lower Na^+/K^+, decreased hydrogen peroxide and membrane injury, and moderated antioxidant enzyme activities indicated that improved internal drainage and salt removal from the root zone played a central role in stress alleviation. The consistent benefits of cut-soiler PSSD across soil types and irrigation water salinity levels confirms its effectiveness as a reclamation strategy. The approach offers a practically feasible, easy-to-execute technique that can be applied at smaller farms without the extra cost of using heavy machinery trenching and pipes. Future studies should evaluate long-term hydraulic persistence and nutrient leaching and standardize the optimum drain spacing using different available crop residues in different agro-climatic conditions in salt-affected regions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy16080779/s1: Figure S1: Seasonal dynamics of root-zone salinity (ECe) under cut-soiler PSSD in saline sandy loam soil under different irrigation water salinity levels; Figure S2: Schematic diagram of construction of simulated cut-soiler PSSD in lysimeter; Table S1: Composition of differential salinity of applied irrigation water; Table S2: Three-way interaction tables for different parameters of pearl millet; Table S3: Three-way interaction tables for different parameters of mustard; Table S4: Multivariate regression analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

PSSD	Preferential shallow subsurface drainage
CS	Cut-soiler
WCS	Without cut-soiler
MDA	Malondialdehyde
SOD	Superoxide dismutase
CAT	Catalase
POX	Peroxidase
APX	Ascorbate peroxidase
ROS	Reactive oxygen species

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