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Cut-soiler-constructed residue-filled preferential shallow sub-surface drainage improves the performance of mustard-pearl millet cropping system in saline soils of semi-arid regions

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Agricultural productivity in semi-arid regions is constrained by soil and
groundwater salinity. This study quantified the desalinization potential of cut-
soiler-constructed preferential shallow sub-surface drainage (PSSD) and its
impact on crop performance in saline agroecologies. The study was
conducted at the Indian Council of Agricultural Research (ICAR)-Central Soil
Salinity Research Institute, Karnal, India, from 2019-2021. The rice residue-filled
PSSD was simulated manually (60 cm depth) in a split-split plot experiment with
saline and normal soil under saline water irrigation (4, 8, and 12 dS m^{-1}). Cut-soiler
PSSD were constructed in the middle of the lysimeter using rice residue
(equivalent to 6 Mg ha^{-1}) as the filling material with an outlet to quantify salt
and water outflow. Pearl millet [*Pennisetum glaucum* L. (R. Br)], variety HHB-197,
and mustard (*Brassica juncea* L.), variety CS-58, were grown in the rainy (*Kharif*)
and winter (*Rabi*) seasons, respectively. The soil salinity profile decreased by
23.3%-58.5% with cut-soiler PSSD in different soils. The decrease in salinity was
associated with increased plant height, dry matter accumulation (DMA), net
assimilation rate (NAR), crop growth rate (CGR), relative growth rate (RGR), leaf
area (LA), and leaf area Index (LAI) in both crops. The pearl millet and mustard
yield increases in the two soil types were 11.6%-43.3% and 26%-36%, respectively
using saline water up to 12 dS m^{-1}. This study concludes that cut-soiler PSSD can
effectively mitigate salinity stress and utilize saline water at the farm scale in salt-
affected semi-arid agro-eco-regions.

GRAPHICAL ABSTRACT
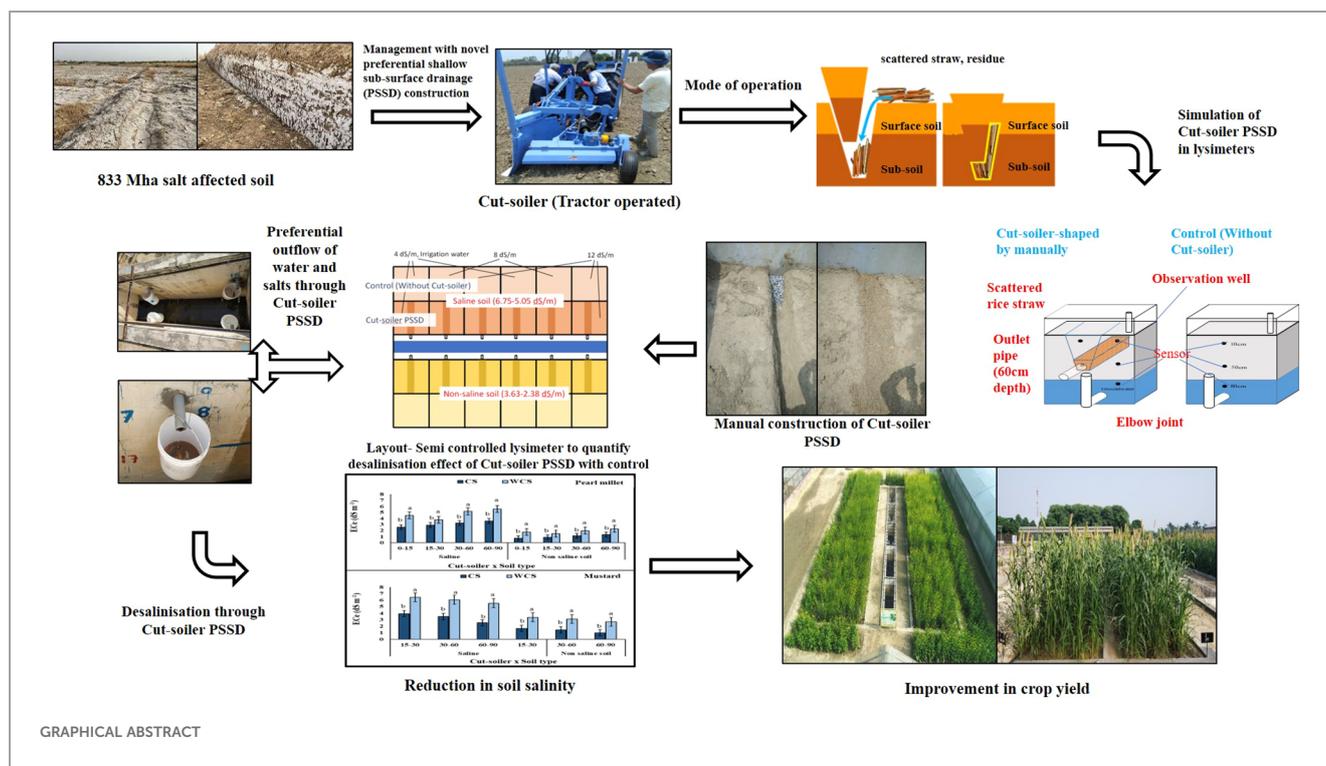
1 Introduction

Food and water security are under threat in many parts of the world from frequent and intense extreme weather events causing drought, floods, and associated loss of vital natural ecosystems (Cooper, 2023; Shrivastava and Kumar, 2015). Approximately 351.5 million hectares (M ha) of saline and 581.0 M ha of sodic soils have given rise to a total of 932.5 M ha of salt-affected soils across the globe (Szabolcs, 1989; FAO, 2017; Pessarakli and Szabolcs, 2019). Globally, US\$12 to 27.3 billion are lost annually due to salinity-associated reductions in crop productivity (Qadir et al., 2014; Wang, 2021). Agricultural and agroecosystem productivity, especially in semi-arid and arid regions worldwide, is challenged by a scarcity of fresh water and secondary salinization (Lakhdar et al., 2009). In India, approximately 6.73 M ha of land is affected by different levels of salinity and sodicity (Sharma et al., 2015). Furthermore, at present, approximately 32%-84% of groundwater in various states is affected by salinity and/or sodicity (Choudhary and Kharche, 2018). The projected effects of climate change also have a direct impact on soil salinization because of upward salt movement under increased temperature conditions. The situation is further worsened in different regions due to the use of poor-quality groundwater for irrigation (Minhas, 1996). Arid to semi-arid climatic conditions and irrigation with saline groundwater without provision of adequate drainage result in an accumulation of salts in the soil profile and pose risks to sustainable crop production (Qadir et al., 2009), environmental health, and financial welfare (Diaz et al., 2021; Wei et al., 2021). Root zone salinity adversely alters the soil solution composition, adversely affecting the nutrient supply capacity and productivity of the soil (Soni et al., 2021; Fu et al., 2020; Dong et al., 2008).

Pearl millet-mustard is one of the important cropping systems in arid and semi-arid regions (Choudhary et al., 2017). Pearl millet (*Pennisetum glaucum* L.), being a drought- and salinity-tolerant, highly vigorous, and quick-growing crop, serves as a staple diet for the vast majority of the population and is an important fodder for livestock in these regions (Krishnamurthy et al., 2007). Mustard [*Brassica juncea* (L.) Czern and Coss.], (2n=36) is also a very important oilseed crop, mainly cultivated for edible oil, in addition to being used as a spice, consumed as a leafy vegetable, and used for condiments and fodder. Nevertheless, the productivity of these two crops is far below their potential in salt-affected conditions in semi-arid regions. A high soil salinity ($10 \, dS \, m^{-1}$) is reported to cause up to ~31% decrease in seed setting and grain yield (GY) (Prakash et al., 2021). The stresses due to the salinity of soil and water contribute to greater yield losses in both seed and oil yields (Singh and Sharma, 2016). Salinity stress significantly reduces plant height and a high Na/K ratio in pearl millet and wheat (Yadav et al., 2020). Similarly, irrigation with saline water of $12 \, dS \, m^{-1}$ led to a 38.7% decrease in pearl millet grain yield (Heidari and Jamshidi, 2011). Salinity stress interferes with plant metabolism through decreased nutrient uptake, impaired photosynthetic machinery, a reduction in the photosynthetic rate, suppressed assimilated partitioning, translocation of photosynthates from the source to the sink, and pre-mature leaf senescence, causing

appreciable decreases in crop growth and yield (Wahid et al., 2005; Tripathi et al., 2010; Soni et al., 2021). Managing root zone salinity within a critical range for the crops by promoting downward salt flux is key to the successful cultivation of moderately salt-tolerant crops in regions underlined by saline groundwater (Rai et al., 2022).

Root zone salinity management primarily focuses on agronomic practices that retard upward flux during the crop season such as mulching, deficit saline water irrigation, and conjunctive use of saline water with good-quality water (Soni et al., 2023). In all these approaches, salts remain in the profile and reappear in the root zone depending upon the evaporative flux. The shallow residue filled cut-drains prepared using a cut-soiler machine were observed to reduce soil salinity and increase cotton and paddy yields after 1 year of operation in salt-affected irrigated fields in Uzbekistan and paddy fields in Japan (Okuda et al., 2018). This residue-filled preferential shallow sub-surface drainage (PSSD) has also shown promise in increasing the yield of the pearl millet and mustard crops in saline soils under irrigation with saline waters in the semi-arid monsoonal climate of India (Neha et al., 2022a, b). These findings suggest that cut-soiler (machine) based residue-filled preferential sub-surface drainage can serve as a remunerative strategy for the sustainable management of saline soil and improve crop production in semi-arid regions where saline groundwater is the only source of irrigation. However, information on the effect of cut-soiler-constructed PSSD on the build-up of salinity in the soil profile and crop growth in a monsoonal climate with different soil and water salinities is scarce. Therefore, we evaluated cut-soiler-constructed PSSD to (i) quantify the effect of cut-soiler PSSD on the changes in soil salinity and moisture content in the soil profile and (ii) assess the effect of change in soil salinity and moisture availability on the physiological processes, growth, and yield of pearl millet-mustard cropping system under saline groundwater irrigation.

2 Materials and methods

2.1 Experimental site

The experiment was conducted in semi-controlled lysimeters during 2019 to 2021 at the ICAR- Central Soil Salinity Research Institute, Karnal, Haryana, India (29°42' N latitude and 76°57' E longitude). The site has a semi-arid subtropical monsoonal climate with an average annual rainfall of 757.6 mm, hot summers (May-June), cold winters (December-January), and a distinct rainy (monsoon) season (June-September). The maximum and minimum mean temperature ranges from 32.7°C to 42.8°C in May-June and 3.4°C to 10.8°C in December-January, respectively. The seasonal weather conditions of the two experimental years are provided in Figure 1.

2.2 Experimental design and treatments details

The study was conducted in a split-split plot design. The treatments comprised two main plots (cut-soiler PSSD and without cut-soiler PSSD), two sub-plots [saline (sandy loam; ECe 6.0 dS m^{-1}) and non-saline (silty clay loam; ECe 3.02 dS m^{-1}) soils], and three levels of irrigation water salinity (4, 8, and 12 dS m^{-1}) in sub-sub plots. In total, these 12 treatment combinations (2 x 2 x 3) were replicated twice in a total of 24 lysimeters of 2.0 m x 2.0 m x 3.0 m (L x W x H), and the layout is depicted in Figure 2. Each lysimeter was separated by a 10 cm thick reinforced cement and concrete (RCC) wall and a polythene sheet lining the wall and the bottom. Pearl millet [*Pennisetum glaucum* L. (R. Br)] variety HHB-197 and mustard (*Brassica juncea* L.) variety CS-58 were grown in the rainy (*Kharif*) and winter (*Rabi*) seasons, respectively. The pearl millet was sown on
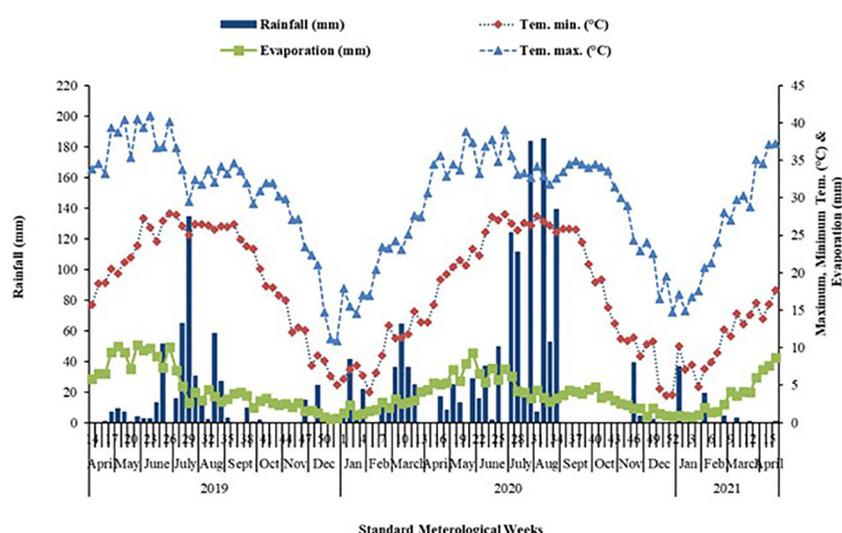

FIGURE 1
Average weekly weather during 2019, 2020, and 2021 (RF, rainfall; Temp.Max., maximum temperature; Temp.Min., minimum temperature).
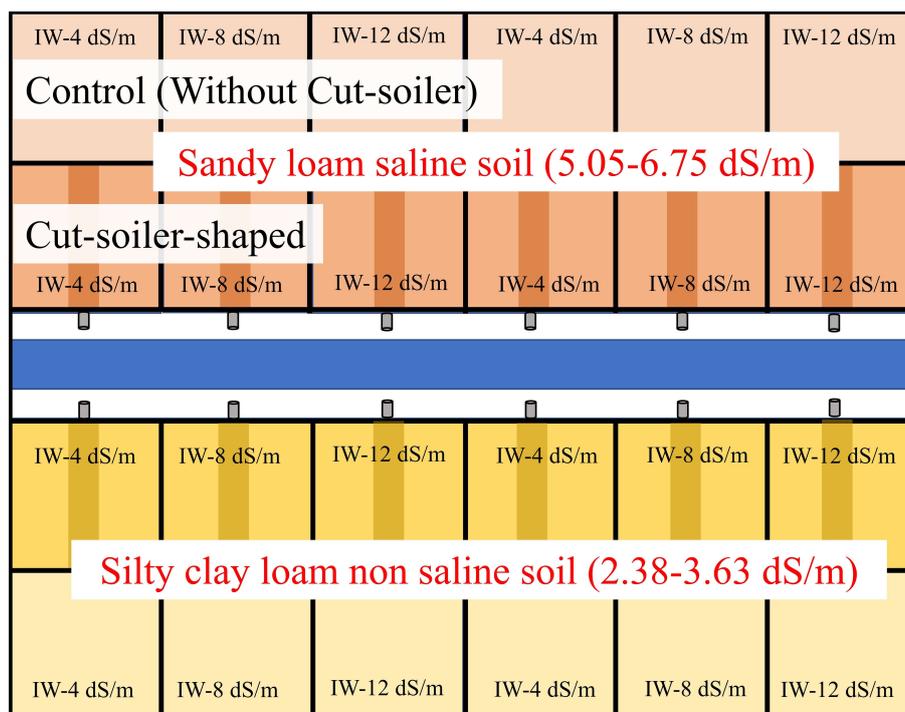
FIGURE 2
Layout of the semi-controlled lysimeter experiment to quantify the desalinization effect of cut-soiler PSSD with a control.

29 July and 14 July in 2019 and 2020, respectively. A uniform seed rate of 4 kg ha^{-1} of pearl millet was used with an inter-row spacing of 45 cm. Sowing was done manually using a hand plow. Thinning was done 20 days after sowing (DAS) to maintain a single plant with a plant-to-plant spacing of 15 cm to avoid competition. CS-58 is a high-yielding variety of Indian mustard that is tolerant of salt (Singh et al., 2019). CS-58 is recommended for saline soils with a salinity level (ECe) of up to 11.0 dS m^{-1} (ICAR-CSSRI::Central Soil Salinity Research Institute). Sowing of mustard was done on 02 November and 23 October in 2019 and 2020, respectively, with a row-to-row distance of 45 cm and a uniform seed rate of 5 kg ha^{-1}. Thinning was done 3-4 weeks after sowing to maintain a plant-to-plant distance of 10-15 cm. One hoeing is done 3-4 weeks after sowing. N: P$_2$O5: K$_2$O at a ratio of 80:40:30 in pearl millet and 80:60:40 kg ha^{-1} in mustard were applied using urea, diammonium phosphate (DAP), and muriate of potash. A full dose of phosphorus (P) and potassium (K), and half dose of nitrogen were applied as the basal dose at the time of sowing and the remaining nitrogen was applied as top dressing 30 days after sowing (vegetative stage) in both crops. The plots were maintained weed-free (by hand weeding and hoeing as and when required) throughout. For the pearl millet, the fungicide Tilt (Propiconazole 25% EC) and Monocrotophos 36% SL insecticide were applied to control fungal diseases and insect pests. In the mustard crop, the Ridomil Gold (Metalaxyl-M 4% + Mancozeb 64% WP) fungicide and the Rogor (Dimethoate 30% EC) insecticide were applied to control the insect pests. Irrigation was scheduled for the identified critical growth stages for mustard and as per the lifesaving water requirement for pearl millet. Saline water

irrigation as per treatments were applied pre-sowing and during the flowering stages of the pearl millet. In the mustard, in addition to pre-sowing irrigation, three irrigations were applied at the vegetative, flowering, and siliqua-formation stages.

2.3 Preparation of lysimeters

The lysimeters were filled with saline sandy loam and non-saline silty clay loam soil collected from representative sites in Nain, Panipat (29°19′7.09′′ to 29°19′10.0′′N latitude and 76°47′30.0′′to 76°48′0.0′′E) and Sitamai, Karnal (29°68′ N and 76°99′E), respectively. Cut-soiler-based residue-filled V shape preferential drains were constructed manually to simulate cut-soiler PSSD at a depth of 60 cm below the soil surface. The cut-soiler PSSD was filled with 2.4 kg/lysimeter rice residue (equivalent to 6 Mg ha^{-1}). The residue-filled preferential shallow sub-surface drains were connected to the outlet provided in a gallery at the same depth (60 cm) in the lysimeter for this purpose. Nylon and gravel filter material were used at the drain outlet connection point of the pipe to avoid clogging. Another outlet at the bottom of the lysimeter maintained the hydraulic head and the water table at the desired depth. The details of the function of cut-soiler PSSD are provided in Neha et al. (2022a). Soil samples were collected 50 cm from the cut-soiler PSSD line in each lysimeter plot at the beginning of the experiment for the initial soil physico-chemical properties such as ECe, pH, texture, hydraulic conductivity, bulk density, and soil moisture (Table 1). The changes in the salinity of the aqueous soil

TABLE 1 Initial soil status of the experimental soil.

Soil property	Saline soil				Heavy-textured soil			
Texture	Sandy loam				Silty clay loam			
Hydraulic conductivity (cm day^{-1})	40.02 ± 9.96				11.23 ± 5.39			
Bulk density	1.57 ± 0.03				1.67± 0.06			
Soil moisture (%) at field capacity	23.45 ± 4.72				25.31 ± 4.29			
Soil moisture (%) at permanent wilting point	8.31 ± 1.02				16.4 ± 5.87			
	Soil depth (cm)							
	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90
pH$_s$	6.80 ± 0.26	7.08 ± 0.20	7.38 ± 0.14	7.29 ± 0.08	7.15 ± 0.17	7.31 ± 0.09	7.54 ± 0.13	7.37 ± 0.09
EC$_e$ (dS m^{-1})	6.75 ± 1.18	6.40 ± 1.65	5.82 ± 1.57	5.05 ± 1.49	3.63 ± 1.82	3.20 ± 1.78	2.88 ± 1.68	2.38 ± 1.84

saturation extract (ECe) under different treatments were measured at the beginning and end of each growing season as per the method described by Richards (1954). The initial soil salinity (EC$_e$) up to 90 cm (0-15, 15-30, 30-60, and 60-90 cm) ranged from 5.05 ± 1.49 to 6.75 ± 1.18 in the saline soil and 2.38 ± 1.84 to 3.63 ± 1.82 dS m^{-1} in the non-saline silty clay loam soil (Table 1). Water with 4, 8, and 12 dS m^{-1} salinity levels was prepared by mixing the non-saline tap water (<0.5 dS m^{-1}) with underground water of 4 and 17 dS m^{-1} collected from Nain (Panipat), India. The EC of the irrigation water was estimated at 25°C using a portable EC Testr11 meter.

2.4 Observations recorded

The height (cm) of three randomly selected plants was measured at the vegetative, flowering, and harvesting stages for the pearl millet and at 30, 60, 90, and 120 DAS for the mustard. Dry matter accumulation (g m^{-2}) of fresh plant samples was estimated by oven drying at 65 ± 5°C until the attainment of a constant weight. The crop growth rate (CGR) (g m^{-2} day^{-1}), relative growth rate (RGR) (mg g^{-1} day^{-1}), and net assimilation rate (NAR) (mg m^{-2} day^{-1}) were calculated as per the formulae given by Radford (1967). The leaf area (LA, cm^2 plant^{-1}) of the detached fully expanded flag leaves was measured using a leaf area meter (CI-203 Wand Leaf Area Meter, WA USA). The leaf area index (LAI) was measured by Sun Scan during mid-day (Tillack et al., 2014) using a CI-203 handheld Laser Leaf Area Meter. Likewise, the average test weight (g) and grain yields (t ha^{-1}) were estimated separately for each treatment. Soil samples were collected at 0-15, 15-30, 30-60, and 60-90 cm depths before sowing and after harvest of each crop and analyzed for EC$_e$ and gravimetric moisture content.

2.5 Statistical analysis

The data generated were subjected to the statistical analyses of variance (ANOVA) technique for split-split plot design using SAS 9.2 software (SAS Institute, 2001). The normality and heterogeneity of the variance were tested using Shapiro–Wilk's and Bartlett's tests, respectively, before performing the ANOVA.

Tukey's test at $p \le 0.05$ was used for pairwise comparisons of different treatments.

3 Results

3.1 Changes in soil salinity and moisture content

The cut-soiler PSSD continuously decreased EC$_e$ from the harvest of the first pearl millet crop in October 2019 to the harvest of the second mustard crop in April 2021 in both soil types (Figure 3). Soil salinity declined by 23.3% to 58.5% in both soil types from its initial values (~6.0 dS m^{-1} in the saline soil and ~3.02 dS m^{-1} in the normal soil) in different soil layers after the pearl millet harvest in October 2019. The decline in salinity was greater in the surface soil (0-15 cm) and layers adjacent (30-60 and 60-90 cm) to the cut-soiler PSSD depth (Figure 3A). In April 2021, after the harvest of the mustard crop, the decline in soil salinity was even greater, 38.88% to 62.92 % in both the soil types with a maximum decrease at the 60-90 cm depth (just below the cut-soiler PSSD depth) (Figure 3D). The soil salinity gradually decreased with time and it was greater in 2020 compared to 2021 in all the soil layers (Figure 3B).

The interaction effect of cut-soiler PSSD and soil type was significant for soil EC$_e$ at the 0-15, 15-30, 30-60, and 60-90 cm depths after the harvest of pearl millet (Figure 3). The treatments without cut-soiler PSSD in the saline soil recorded significantly higher EC$_e$ (3.77, 4.49, 5.17, and 5.56 dS m^{-1}) at 0-15, 15-30, 30-60, and 60-90 cm soil depths, respectively, in comparison to that of the cut-soiler PSSD treatment observed after harvest of both the crops. Again, the without cut-soiler PSSD and the saline sandy loam soil treatment recorded significantly higher EC$_e$ (6.43, 6.06, and 5.53 dS m^{-1}) at the 15-30, 30-60, and 60-90 cm soil depths (Figure 3D).

Cut-soiler PSSD and the salinity of the irrigation water also had a significant interaction effect on the observed soil salinity after both crops were harvested (Figures 3C, F). In general, the soil salinity was lowest with cut-soiler PSSD with the application of 4 dS m^{-1}; ECe increased progressively with an increase in irrigation water salinity at all the soil depths (0-15, 15-30, 30-60, and 60-90 cm) and was the highest in the 12 dS m^{-1} EC$_{iw}$ without the cut-soiler PSSD treatment. The changes in gravimetric
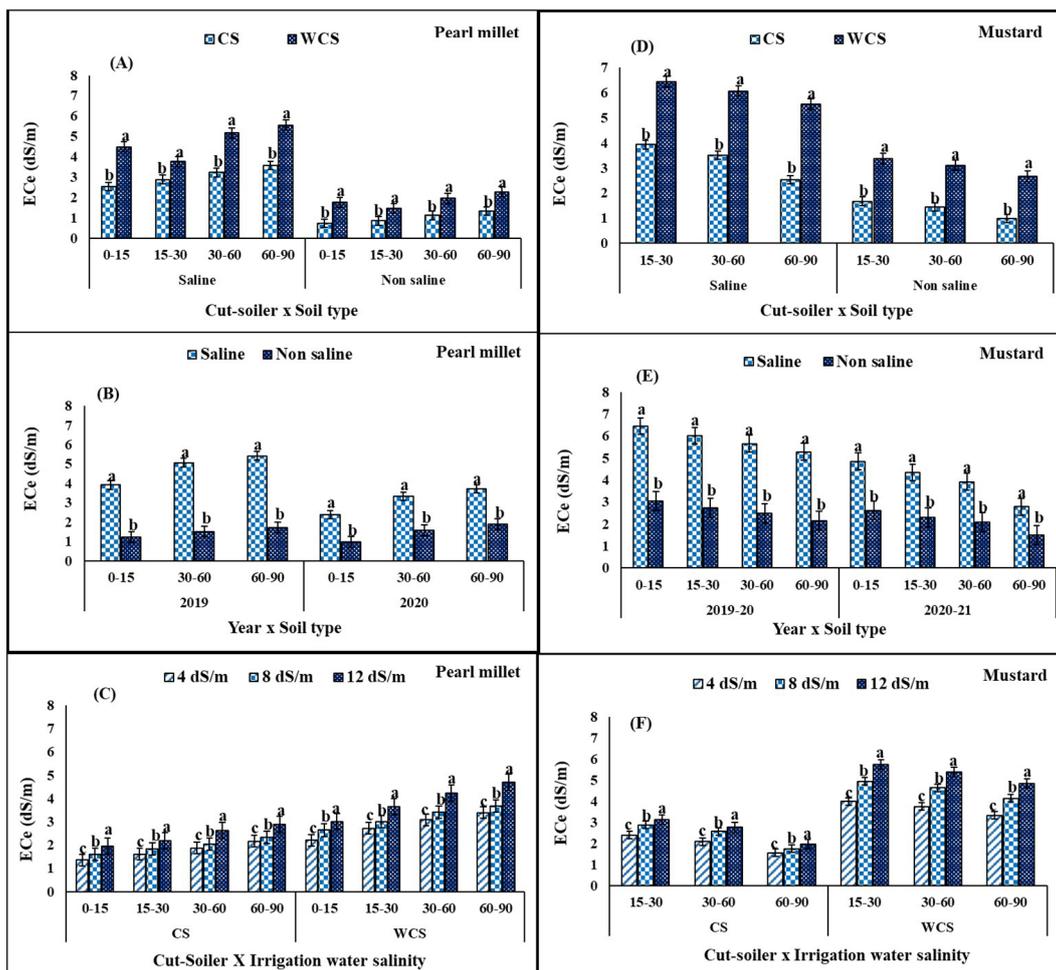
FIGURE 3
Change in soil salinity at different soil depths after the harvest of pearl millet under **(A)** cut-soiler PSSD x soil type, **(B)** year x soil type, and **(C)** Cut-soiler PSSD x irrigation water salinity; and after the harvest of mustard under **(D)** cut-soiler PSSD x soil type, **(E)** year x soil type, and **(F)** cut-soiler PSSD x irrigation water salinity. Bars with standard error at each depth are significantly different ($P \leq 0.05$); the capped line on each bar is the standard error. CS, cut-soiler PSSD; WCS, control without cut-soiler PSSD; data is the mean of 2 years. The letter (a,b,c...) on the value bar of figure indicate significance of differences based on LSD.

soil moisture content (%) were significantly higher before sowing the pearl millet and mustard crops than at their harvest (Figure 4). Relatively lower soil moisture content was recorded in the cut-soiler PSSD treatments compared to the treatments without cut-soiler PSSD at each sampling i.e., before sowing and after harvest of the pearl millet crop (19.38% and 14.26%) and the mustard crop (18.17% and 12.96%) (Figure 4).

3.2 Biomass accumulation and crop growth

The soil salinity negatively affected the growth and dry matter accumulation (DMA) of both crops. Likewise, increasing the salinity of the irrigation water also decreased the plant height and DMA of the pearl millet and mustard. However, the cut-soiler PSSD moderated the negative impact of salinity and the plant height of the pearl millet was greater at the vegetative, flowering, and harvesting stages in the cut-soiler PSSD treatment (Table 2).

Similarly, the mustard plant height at 30, 60, 90, and 120 DAS, and at harvest was also significantly increased by 7% to 30 % in the cut-soiler PSSD plots compared to those without cut-soiler PSSD. The DMA of the pearl millet also significantly increased by 12.07%, 19.45%, 21.75%, and 23.75% at all four studied stages, respectively, (Table 3) with cut-soiler PSSD compared to without cut-soiler PSSD. Similarly, the mustard crop also had greater a DMA at all the growth stages in the cut-soiler PSSD plots compared to those without cut-soiler PSSD.

The NAR of both crops at different growth stages was low in the saline soil and was significantly decreased with an increase in irrigation water salinity (Table 4). The cut-soiler PSSD improved the NAR of both crops and a relatively increased NAR at all growth stages was recorded in the pearl millet with cut-soiler PSSD in comparison to that without cut-soiler PSSD (control). However, the cut-soiler PSSD effect was apparent only at the vegetative to flowering stage of the mustard. Similarly, the effect of soil type on NAR was apparent only at the flowering to reproductive stage with higher values for the non-saline
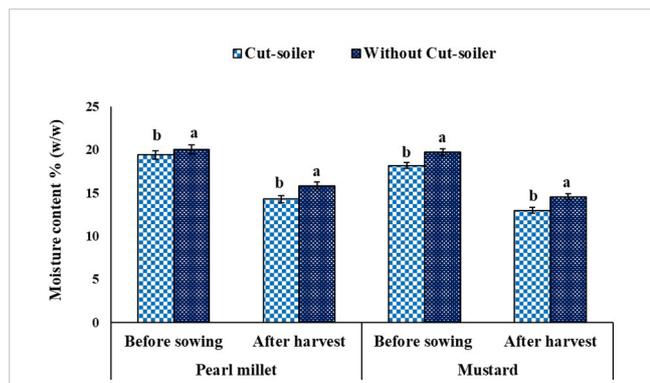
FIGURE 4
Effect of cut-soiler PSSD on soil moisture content (%) before sowing and after harvesting of pearl millet and mustard. Bars with standard error at each depth are significantly different ($P \leq 0.05$); the capped line on each bar is the standard error. CS, cut-soiler PSSD; WCS, control without cut-soiler PSSD; data is the mean of 2 years. The letter (a,b…) on the value bar of figure indicate significance of differences based on LSD.

soil. The effect of irrigation water salinity was evident only for 12 dS m^{-1} at the vegetative to flowering stage (Table 4).

The cut-soiler PSSD plots recorded higher CGR for the pearl millet at all three growth stages (Figure 5A). A higher CGR of the crop at all three successive growth stages was observed in the non-saline soil compared to the saline soil (Figure 5B). Among the different irrigation water salinity treatments, the maximum CGR was found in the 4 dS m^{-1} treatment, followed by 8 dS m^{-1} and 12 dS m^{-1} (Figure 5C). Similarly, the cut-soiler PSSD plots had a significantly higher CGR for

the mustard crop compared to those without cut-soiler PSSD (Figure 5A). The non-saline soil had a higher CGR compared to the saline soil (Figure 5B). The CGR was significantly decreased with an increase in irrigation water salinity (Figure 5C). Similar to CGR, the RGR at different growth stages of pearl millet had higher values in the cut-soiler PSSD treatments compared to those without cut-soiler PSSD. The non-saline soil recorded a higher RGR at all three growth stages compared to the saline soil (Figure 5E). Among the different irrigation water salinity treatments, increasing the water salinity significantly reduced the RGR by 3.87%, 7.43%, and 1.03% under 8 dS m^{-1} EC$_{iw}$ and by 7.93%, 10.03%, and 1.45 % under 12 dS m^{-1} EC$_{iw}$ in the respective growth stages (Figure 5F). The mustard crop also recorded similar results for cut-soiler PSSD, non-saline soil, and irrigation water salinity (Figures 5D–F).

The cut-soiler PSSD significantly increased pearl millet LA by 27.15% and 23.55 % in the vegetative and reproductive stages, respectively. Of the two soil types, the non-saline soil had significantly higher LA compared to the saline soil at both the studied stages (Table 5). A progressive increase in irrigation water salinity, from 4 dS m^{-1} to 12 dS m^{-1}, decreased LA significantly. In the mustard crop, cut-soiler PSSD resulted in a significant increase of 10.72% and 13.65% in LA in both the studied stages respectively compared to the treatment without cut-soiler PSSD (Table 5). Similarly, of the two soil types, the non-saline soil had significantly higher LA compared to the saline soil in the vegetative (100.30 and 88.97 cm^{-2}) and reproductive (140.99 and 137.79 cm^{-2}) stages. The LA decreased significantly with increasing salinity of irrigation water. The cut-soiler PSSD and non-saline soil plots recorded a higher LAI than those without cut-soiler PSSD and saline soil (Table 5).

TABLE 2 Effect of cut-soiler PSSD, soil type, and irrigation water salinity on the plant height (cm) of pearl millet and mustard crops at various growth stages.

	Pearl millet			Mustard				
	Vegetative stage	Flowering stage	Harvesting stage	30 DAS	60 DAS	90 DAS	120 DAS	Harvesting stage
Cut-soiler PSSD								
Cut-soiler PSSD	94.72[A]	178.71[A]	205.04[A]	17.82[A]	48.26[A]	100.04[A]	153.39[A]	196.12[A]
Without Cut-soiler PSSD	86.63[B]	169.73[B]	192.32[B]	13.75[B]	37.22[B]	82.46[B]	140.26[B]	183.99[B]
CD (*P*=0.05)	0.89 ± 0.28	0.38 ± 0.12	1.17 ± 0.37	0.26 ± 0.08	1.18 ± 0.37	2.31 ± 0.73	1.64 ± 0.51	0.68 ± 0.21
Soil type								
Saline soil	87.96[B]	171.63[B]	195.69[B]	14.62[B]	39.79[B]	86.47[B]	143.28[B]	186.45[B]
Heavy textured soil	93.39[A]	176.82[A]	201.68[A]	16.96[A]	45.69[A]	96.03[A]	150.38[A]	193.66[A]
CD (*P*=0.05)	0.42 ± 0.2	0.2 ± 0.1	0.37 ± 0.18	0.14 ± 0.07	0.33 ± 0.16	0.43 ± 0.21	0.58 ± 0.28	0.46 ± 0.22
Irrigation water salinity (dS m^{-1})								
4 dS m^{-1}	92.81[A]	176.19[A]	201.02[A]	16.70[A]	44.53[A]	95.60[A]	149.27[A]	192.78[A]
8 dS m^{-1}	90.86[B]	174.29[B]	198.96[B]	15.66[B]	42.66[B]	90.64[B]	146.78[B]	190.16[B]
12 dS m^{-1}	88.36[C]	172.19[C]	196.07[C]	15.01[C]	41.03[C]	87.50[C]	144.44[C]	187.23[C]

Data are the mean over 2 years and means with different letters within the same column are significantly different on the basis of critical differences.

TABLE 3 Effect of cut-soiler PSSD, soil type, and irrigation water salinity on the dry matter accumulation (g m^{-2}) of pearl millet and mustard crops at various growth stages.

Treatments/ Traits	Pearl millet				Mustard			
	Tillering stage	Vegetative stage	Reproductive stage	Harvesting stage	30 DAS	60 DAS	90 DAS	Harvesting stage
Cut-soiler PSSD								
Cut-soiler PSSD	332.88^A	562.89^A	885.21^A	982.66^A	268.72^A	490.14^A	802.55^A	877.08^A
Without cut-soiler PSSD	297.04^B	471.22^B	727.05^B	794.05^B	232.79^B	398.47^B	643.94^B	687.80^B
CD (P=0.05)	2.07 ± 0.65	0.26 ± 0.08	1.59 ± 0.5	2.62 ± 0.82	2.17 ± 0.68	0.26 ± 0.08	0.75 ± 0.24	1.97 ± 0.62
Soil type								
Saline soil	309.19^B	500.51^B	772.59^B	848.06^B	245.03^B	427.76^B	690.00^B	742.48^B
Heavy-textured soil	320.73^A	533.60^A	839.66^A	928.65^A	256.48^A	460.85^A	756.48^A	822.40^A
CD (P=0.05)	0.94 ± 0.45	1.15 ± 0.55	1.73 ± 0.83	2.63 ± 1.26	0.97 ± 0.47	1.15 ± 0.55	1.31 ± 0.63	2.27 ± 1.09
Irrigation water salinity (dS m^{-1})								
4 dS m^{-1}	330.89^A	553.27^A	885.96^A	976.80^A	266.78^A	480.52^A	802.78^A	871.56^A
8 dS m^{-1}	321.50^B	527.12^B	813.39^B	896.36^B	257.25^B	454.37^B	730.92^B	790.11^B
12 dS m^{-1}	292.49^C	470.78^C	719.03^C	791.90^C	228.24^C	398.03^C	636.03^C	685.65^C

Data are the mean over 2 years and means with different letters within the same column are significantly different on the basis of critical differences.

TABLE 4 Effect of cut-soiler PSSD, soil type, and irrigation water salinity on the net assimilation rate (g m^{-2} d^{-1}) of pearl millet and mustard crops at various growth stages.

Treatments/Traits	Pearl millet		Mustard	
	Net assimilation rate (g m^{-2} d^{-1})		Net assimilation rate (g m^{-2} d^{-1})	
	Tillering to vegetative stage	Reproductive to harvesting stage	Vegetative to flowering stage	Flowering to reproductive stage
Cut-soiler PSSD				
Cut-soiler PSSD	0.123^A	0.038^A	0.089^A	0.827
Without cut-soiler PSSD	0.109^B	0.032^B	0.076^B	0.821
CD (P=0.05)	0.01	0.01	0.01	NS
Soil type				
Saline soil	0.111^B	0.033^B	0.083	0.802^B
Heavy-textured soil	0.118^A	0.037^A	0.087	0.845^A
CD (P=0.05)	0.01	0.01	NS	0.01 ± 0.01
Irrigation water salinity (dS m^{-1})				
4 dS m^{-1}	0.125^A	0.037^A	0.087^A	0.837
8 dS m^{-1}	0.118^B	0.036^B	0.080^A	0.828
12 dS m^{-1}	0.106^C	0.033^C	0.076^B	0.821

Data are the mean over 2 years and means with different letters within the same column are significantly different on the basis of critical differences.
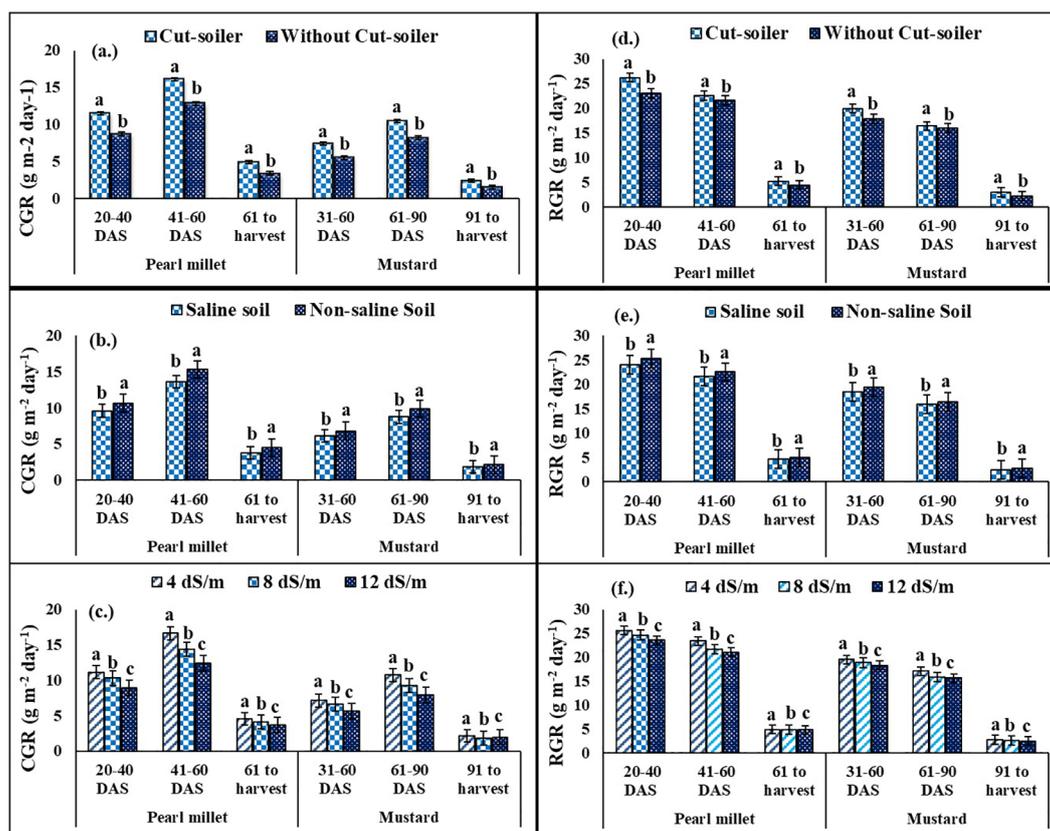
FIGURE 5
Effect of cut-soiler PSSD, soil type, and irrigation water salinity on crop growth rate (CGR) **(A–C)** and relative growth rate (RGR) **(D–F)** of pearl millet and mustard crops at various growth stages. Bars with standard error at each depth are significantly different ($P \leq 0.05$); the capped line on each bar is the standard error. CS, cut-soiler PSSD; WCS, control without cut-soiler PSSD; data is the mean of 2 years. The letter (a,b…) on the value bar of figure indicate significance of differences based on LSD.

However, increasing the salinity of irrigation water reduced the LAI of both crops.

3.3 Na:K ratio

The cut-soiler PSSD treatment caused a significant decrease in the Na:K ratio in pearl millet grain and stover compared to the treatment without cut-soiler PSSD (Figure 6). An increase in irrigation water salinity significantly increased the Na:K ratio in the grain and stover of the pearl millet (Figure 6). Similarly, in the mustard, the Na:K ratio in the seeds was lower in the cut-soiler PSSD treatment compared to the treatment without cut-soiler PSSD. The non-saline soil had a lower Na:K ratio in seeds compared to the saline soil. However, increasing the salinity level of the irrigation water significantly increased the Na:K ratio in seeds. A similar Na:K ratio trend was observed in mustard straw.

3.4 Grain/seed yield and test weight

The grain/seed yield of both crops significantly increased in the treatment with cut-soiler PSSD and non-saline soil but decreased with

an increase in the salinity of the irrigation water. The combined interactive effect of all three factors was also evident during the two study years. Cut-soiler PSSD, in both the saline and non-saline soils, resulted in an increased yield of pearl millet by 26.08% and 20.27% (2019) and 43.26% and 11.62% (2020), and of mustard by 36% and 26% (both years), respectively. The highest pearl millet grain yield (4.61 t ha^{-1}) was recorded in a cut-soiler PSSD treatment in non-saline soil in 2020 and the lowest (2.53 t ha^{-1}) was in a treatment without cut-soiler PSSD in saline soil in 2019 (Figure 7A). The interaction effect of cut-soiler PSSD, soil type, and irrigation water salinity was also found positive (Figure 7B). The highest pearl millet grain yield (4.72 t ha^{-1}) was obtained in a cut-soiler PSSD plot with non-saline soil and irrigation with 4 dS m^{-1} salinity water and declined with increment in soil and irrigation water salinity. The lowest yield (2.24 t ha^{-1}) was recorded in treatment without cut-soiler PSSD with saline soil and the application of 12 dS m^{-1} salinity irrigation water. The effect of saline water irrigation treatments was also found significant ($P=<0.0001$), as the pearl millet yield decreased with increased salinity level of the applied irrigation water. In the case of the mustard crop, the interaction effect of cut-soiler PSSD and irrigation water salinity was significant for seed yield (Figure 7D). Seed yield was the highest (3.01 t ha^{-1}) in a cut-soiler PSSD plot with an irrigation water salinity level of 4 dS m^{-1} while it was the lowest (2.0 t ha^{-1}) in a treatment without cut-soiler PSSD and

TABLE 5 The effect on leaf area and leaf area index of pearl millet and mustard crops of cut-soiler PSSD, soil type, and irrigation water salinity at various growth stages.

Treatments/ Traits	Pearl millet					Mustard					
	Leaf area (cm^2)		Leaf area index			Leaf area (cm^2)		Leaf area index			
	Vegetative	Reproductive	Vegetative	Flowering	Reproductive	Vegetative	Reproductive	30 DAS	60 DAS	90 DAS	120 DAS
Cut-soiler PSSD											
Cut-soiler PSSD	123.42[A]	174.57[A]	0.86[A]	3.27[A]	3.01[A]	99.45	148.2[A]	0.30[A]	0.81[A]	2.05[A]	1.21[A]
Without cut-soiler PSSD	97.06[B]	141.29[B]	0.82[B]	3.03[B]	2.79[B]	89.82	130.4[B]	0.24[B]	0.69[B]	1.62[B]	1.06[B]
CD (*P=0.05*)	5.87 ± 2.4	3.74 ± 1.5	0	0.01 ± 0	0	NS	6 ± 1.88	0.01	0.01	0.04 ± 0.01	0.02 ± 0.01
Soil type											
Saline soil	104.11[B]	154.86[B]	0.83[B]	3.09[B]	2.84[B]	88.97[B]	137.7[B]	0.25[B]	0.71[B]	1.84	1.06[B]
Heavy-textured soil	116.37[A]	161.00[A]	0.85[A]	3.21[A]	2.96[A]	100.30[A]	140.99[A]	0.28[A]	0.79[A]	1.84	1.20[A]
CD (*P=0.05*)	3.64 ± 1.8	3.86 ± 1.9	0	0	0	2.25 ± 1.0	1.7 ± 0.8	0.01	0.01	NS	0.01
Irrigation water salinity (dS m^{-1})											
4 dS m^{-1}	122.80[A]	177.61[A]	0.85[A]	3.19[A]	2.94[A]	103.26[A]	149.8[A]	0.28[A]	0.78[A]	1.88[A]	1.17[A]
8 dS m^{-1}	110.05[B]	157.22[B]	0.84[B]	3.14[B]	2.90[B]	92.79[B]	137.6[B]	0.27[B]	0.75[B]	1.84[B]	1.13[B]
12 dS m^{-1}	97.87[C]	138.96[C]	0.83[C]	3.12[C]	2.86[C]	87.86[C]	130.6[C]	0.26[C]	0.72[C]	1.79[C]	1.10[C]

Data are the mean over 2 years and means with different letters within the same column are significantly different on the basis of critical differences.

a 12 dS m^{-1} salinity level for the irrigation water (Figure 7D). Similarly, cut-soiler PSSD and soil type also had a positive interaction effect on the seed yield of mustard (Figure 7E). The treatment with cut-soiler PSSD in non-saline soil produced the highest seed yield (2.89 t ha^{-1}) and the treatment without cut-soiler PSSD in saline soil resulted in the lowest (1.98 t ha^{-1}) seed yield.

A significantly higher test weight for pearl millet was recorded in the cut-soiler PSSD plots (9.98 g) than in the control (9.33 g) and in non-saline soil (9.80 g) compared to the saline soil (9.51 g)

(Figure 8). Heavier grains were produced under an EC$_{iw}$ of 4 dS m^{-1} (9.82 g) followed by an EC$_{iw}$ of 8 dS m^{-1} (9.65 g) and an EC$_{iw}$ of 12 dS m^{-1} (9.49 g). For the mustard crop, a significantly higher test weight was recorded in the cut-soiler PSSD plots (5.20 g) compared to those without cut-soiler PSSD (4.86 g), and in non-saline soil (5.15 g) compared to saline soil (4.90 g). Among the different irrigation water salinity levels, an EC$_{iw}$ of 4 dS m^{-1} produced heavier grains (5.11 g) followed by an EC$_{iw}$ of 8 dS m^{-1} (5.03 g), and an EC$_{iw}$ of 12 dS m^{-1} (4.95 g).
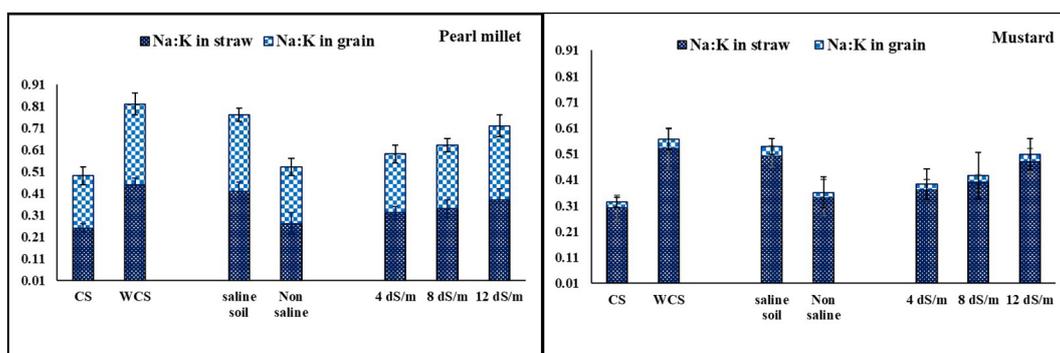
FIGURE 6
Effect of cut-soiler PSSD, soil type, and irrigation water salinity on Na:K ratio of pearl millet and mustard crops. Bars with standard error at each depth are significantly different (*P ≤ 0.05*); the capped line on each bar is the standard error. CS, cut-soiler PSSD; WCS, control without cut-soiler PSSD; data is the mean of 2 years.

3.5 Correlation studies

The growth traits were associated either positively or negatively among themselves and with yield traits and ECe (Figure 9). In the pearl millet, grain yield had a strong positive correlation with plant growth traits such as plant height, dry matter accumulation, crop growth rate, relative growth rate, net assimilation rate, leaf area index, leaf area, and thousand-seed weight (r = 0.63-0.85), while it was negatively correlated with the Na:K ratio (r = -0.63). Similarly, thousand-seed weight was also positively correlated with plant height, dry matter accumulation, crop growth rate, relative growth rate, net assimilation rate, leaf area index, and leaf area (r = 0.61-0.97), while it was negatively correlated with the Na:K ratio (r = -0.57) The soil salinity was negatively correlated with pearl millet grain yield (r = -0.64) and

all other growth parameters and positively associated with the Na: K ratio (r = 0.71).

Also, there was a strong correlation between growth and yield traits in the mustard crop. The grain yield was positively correlated with plant height, dry matter accumulation, crop growth rate, relative growth rate, net assimilation rate, leaf area index, leaf area, and thousand-seed weight (r = 0.67-0.95), but was negatively correlated with the Na:K ratio (r = -0.77). Likewise, thousand-seed weight also showed a positive correlation with plant height, dry matter accumulation, crop growth rate, relative growth rate, net assimilation rate, leaf area index, and leaf area (r = 0.64-0.93), while it was negatively correlated with the Na:K ratio (r = -0.86). The soil salinity was negatively correlated with mustard grain yield (r = -0.81) and all other growth parameters and positively associated with the Na:K ratio (r = 0.92) (Figure 9).
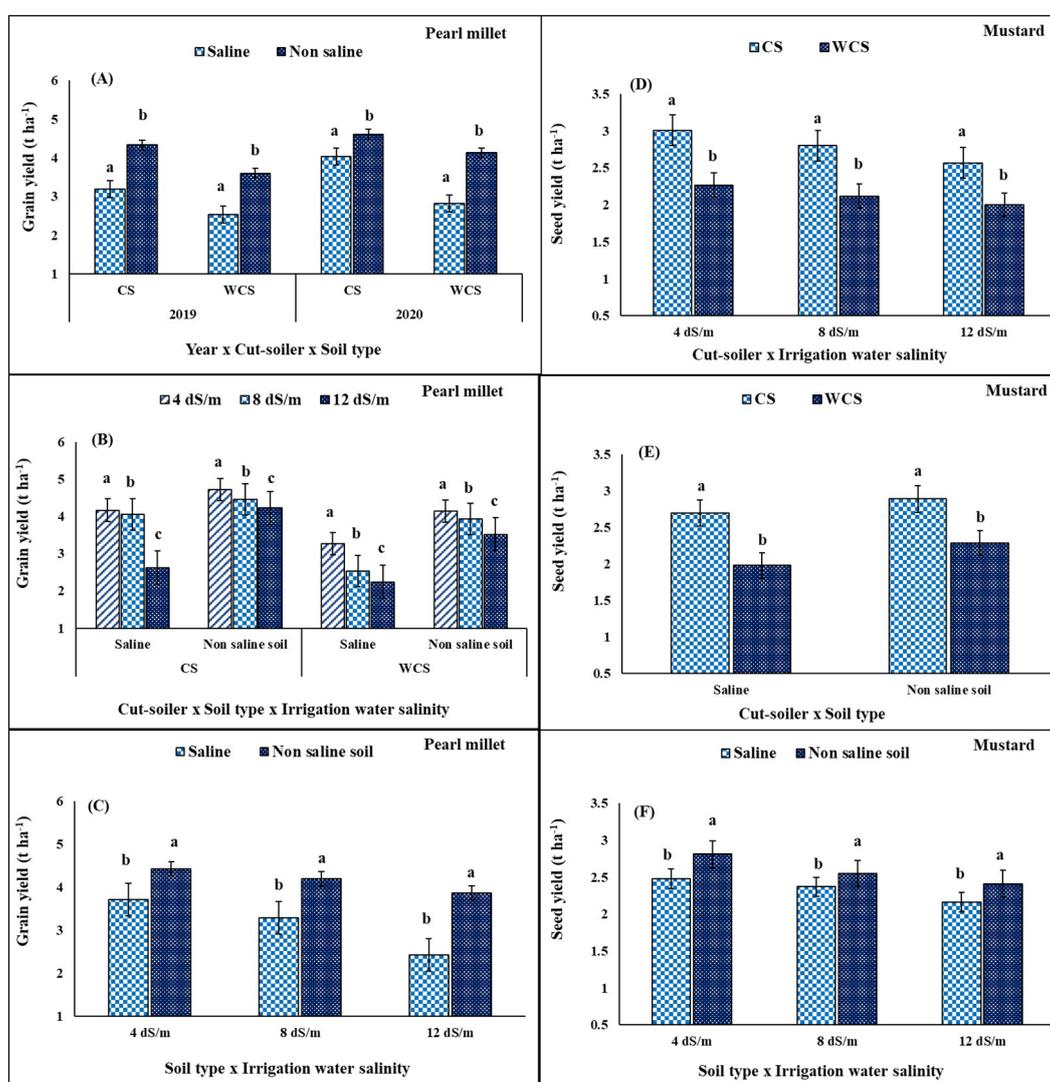

FIGURE 7
Interaction effect of cut-soiler PSSD x soil type x irrigation water salinity on the grain/seed yield of pearl millet and mustard crops at various growth stages. Bars with standard error at each depth are significantly different (P ≤ 0.05); the capped line on each bar is the standard error. CS, cut-soiler PSSD; WCS, control without cut-soiler PSSD; data is the mean of 2 years. The letter (a,b...) on the value bar of figure indicate significance of differences based on LSD.
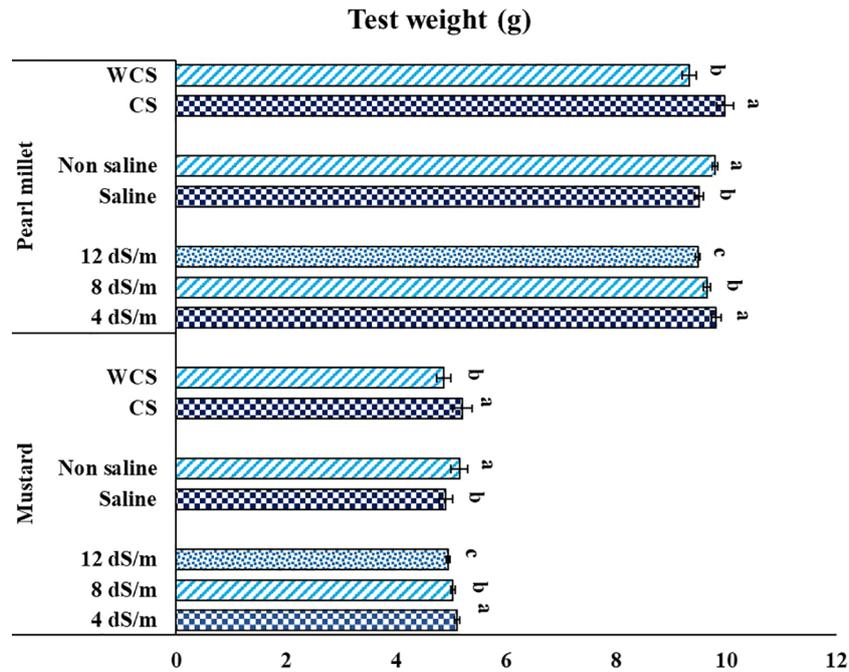
FIGURE 8
Effect of cut-soiler PSSD, soil type, and irrigation water salinity on test weight (g) of pearl millet and mustard crops. Bars with standard error at each depth are significantly different ($P \leq 0.05$); the capped line on each bar is the standard error. CS, cut-soiler PSSD; WCS, control without cut-soiler PSSD; data is the mean of 2 years. The letter (a,b...) on the value bar of figure indicate significance of differences based on LSD.

4 Discussion

4.1 Desalinization effect of cut-soiler PSSD on different irrigation water salinities

Salinity stress largely increases through the interplay of inherent soil salinity, drainage congestion, salinity of irrigation water, and the sensitivity of any crop and its growth stages (Minhas, 1996; Okuda et al., 2018; Yadav et al., 2020; Chakraborty et al., 2016). Hydraulic conductivity, the range of moisture retention, and the moisture release characteristics of any textural class of soil govern its drainage function and leaching fraction (Feng et al., 2019). Whereas the total salt accumulation in the soil profile is a consequence of its drainage function and leaching fraction, and
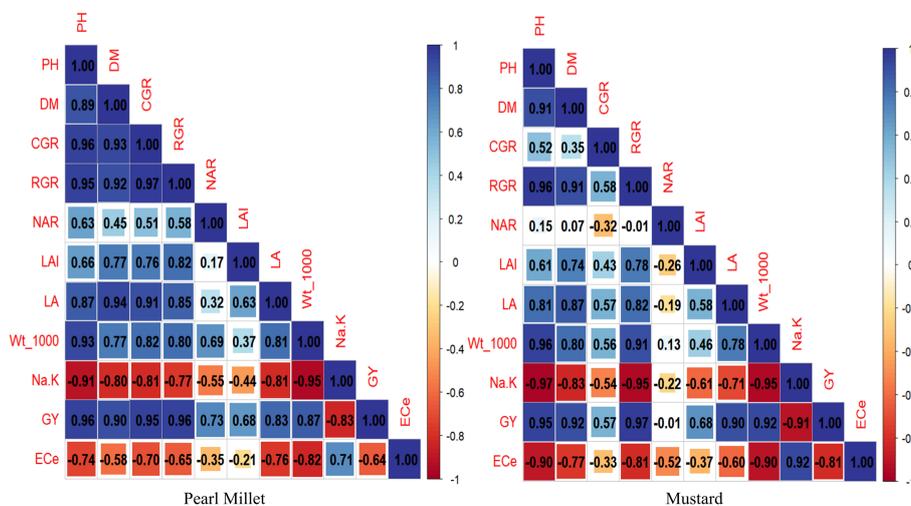

FIGURE 9
Pearson's correlation coefficients among the growth and yield traits of pearl millet and mustard. The color of the boxes reflects the strength of the correlation. The correlation coefficients represent the mean value of pooled measurements from two growing seasons; PH, plant height; DM, dry matter accumulation; CGR, crop growth rate; RGR, relative growth rate; NAR, net assimilation rate; LAI, leaf area index; LA, leaf area; 1000 wt, 1000-grain weight; Na/K, Na:K ratio; GY, Grain Yield; ECe, soil salinity.

the quality of irrigation water or rainfall available for crop production (Sharma and Tyagi, 2004). The balance of the upward and downward salt flux is the result of salt accumulation in the soil solution and the associated proportionate osmotic stress (Lu et al., 2018). The osmotic stress affects the water and nutrient uptake (Yadav et al., 2007; Sarker and Oba, 2020), plant cellular constituents (Silva et al., 2015), physiological processes (Manjili et al., 2012), and growth and production of crops (Alzahrani et al., 2019). The salt movement equilibria in any agroclimatic conditions are modified by the introduction of management practices to tilt the equilibria towards low osmotic stress and better plant-growing conditions. The installation of properly designed subsurface drainage systems can effectively manage the adverse effects of salinity stress (Bundela et al., 2016; Islam et al., 2022). However, such approaches involve a huge cost and require a community approach for large-scale installation. Residue-filled cut-soiler-constructed PSSD has been found to be effective in removing salt from the surface soil (Neha et al., 2022a, b; Okuda et al., 2018). Our results from a present study also showed an appreciable decrease in surface salinity through the lateral flow of salt from the drainage line. In the semi-arid monsoonal climate of the western IGP, salt moves upward and downward depending on the rainfall and evaporative flux (Soni et al., 2021). The use of PSSD in these soils provides an outlet for the net removal of salt through drainage effluents. The repeated cycle of salt movement in the surface soil followed by leaching with rain or irrigation water leads to a decrease in the salinity of the soil profile. This was evident from the decrease in salinity in the soil up to 90 cm in depth and the associated effects on the growth and biomass production of both crops in a pearl millet-mustard cropping system. The salinity of the soil profile is the outcome of salt addition and loss from the system. This was the reason for slightly greater salinity in the soil profile of the PSSD plots irrigated with water with higher salinity. The associated improvement in the soil solution composition, nutrient availability, and plant rhizosphere conditions also resulted in higher growth and production for both crops. This magnitude of reduction in the soil salinity of the root zone was equivalent to a 44%-49% reduction observed in the third year after the installation of pipe SSD (Bundela et al., 2016; Islam et al., 2022; Raju et al., 2016). Similarly, Lu et al. (2018) also reported that maize stalk-filled SSD was quite efficient in removing salt and water from the crop's root zone.

4.2 Changes in soil salinity and moisture in different soil types

Relatively less soil moisture was observed in the cut-soiler PSSD plots in both seasons. Drainage water outflow carrying soluble salts that lower soil salinity in both types of soil under different levels of irrigation water salinity leads to the lowering of the water potential because of its low osmotic potential (Yadav et al., 2007). Therefore, the plant-utilizable water content that was in the field capacity range and permanent wilting point was relatively greater in the PSSD plots compared to the non-PSSD plots under both soil conditions due to the removal of extra water by PSSD through lateral drainage (Singh and

Sharma, 2016). Rice residue-filled cut-soiler PSSD caused higher conducive soil moisture with lower salinity stress in both textural class soils and at different salinity levels of irrigation water. Such an improvement in the aeration and maintenance of optimum moisture during germination and the growth cycle of both crops increased crop germination, root growth, metabolic activities, growth, and overall performance (Neha et al., 2022a). The soil effect on the plant performance was mainly associated with higher hydraulic conductivity and a narrower range of moisture retention/release constants. The moisture constant at the field capacity and permanent wilting point of sandy loam saline soil and silty clay loam soil were 22.1 ± 3.2 and 8.3 ± 0.6%, and 26.2 ± 2.8 and 15.6 ± 1.4%, respectively. This led to a relatively higher reduction in soil salinity (up to 43.42%) but a lower soil moisture content in the sandy loam compared to the silty clay loam soil. Kahlown et al. (2009) found that soil EC and ESP increased by 2.2 dS m^{-1} and 14.8% in coarse, and 9.0 dS m^{-1} and 26.3% in fine-textured soil when high SAR (16) saline water (6.2 dS m^{-1}) was used for irrigation in a mustard crop. Similarly, Ragab et al. (2008) and Chaudhry et al. (2001) recorded a progressive increase in soil EC with increasing levels of irrigation water salinity. Such favorable conditions under PSSD increased crop germination, root growth, metabolic activities, growth, and overall performance (Neha et al., 2022a, b). A progressive increase in the leaching of salts under cut-soiler PSSD during consecutive rainy seasons resulted in a relative decrease in salinity with every season, leading to an increased yield of both crops in the second year (Okuda et al., 2018; Chiba et al., 2012; Kaneko et al., 2002). The use of cut-soiler PSSD in saline sandy loam soils in India and shallow-cut drains in salt-affected fields in Uzbekistan have been reported to result in consistent salt removal and consequently better growth and yield of pearl millet, mustard, and cotton (Neha et al., 2022c, d; Okuda et al., 2018).

4.3 Effect of salinity management on crop performance

Excess soluble salts in the soil profile induce an adverse osmotic effect that reduces the uptake of water (Yadav et al., 2007) with a lower but selective accumulation of ions and nutrients (Sarker and Oba, 2020). Salinity stress also leads to a progressive increase in excess accumulation of Na$^+$ in the cytosol (Sarker and Oba, 2020) and a reduction in the biosynthesis of the chlorophyll protein-lipid complex and photosynthesis efficiency (Manjili et al., 2012). The application of higher salinity irrigation water also causes more negative osmotic/ water potential in the soil profile, which in turn decreases the uptake of both water and nutrients, thereby causing an ionic imbalance and toxicity in plants. All these factors cause impairment of different physiological and biochemical processes, which ultimately cause reduced plant growth and production (Yadav et al., 2020; Soni et al., 2021). Increasing the salinity of irrigation water increased the Na:K ratio and decreased the growth, yield, and their attributes in both crops as was also reported previously in *Brassica juncea* (Kumar et al., 2005) and pearl millet (Mostafa et al., 2012). The residue-filled cut-soiler PSSD in this study reduced salinity stress and lowered the Na:K ratio in plants of both crops. The inhibitory effect of higher salinity levels of irrigation water on yield was caused mainly by

osmotic shock (Nadaf et al., 2010), ion toxicity (Makarana et al., 2017), and nutritional imbalance (Yadav et al., 2020) which reduced photosynthetic activity and other physiological processes (Kumar et al., 2017; Ali and Awan, 2004). The poor seed yield in the saline environment could be also due to salt-induced shrinkage and even complete damage of chloroplasts (Manjili et al., 2012), a decrease in photosynthates in the phloem (Flowers et al., 1991), and water deficiency in the pearl millet-mustard growing regions (Singh and Panda, 2011). However, rice residue-filled cut-soiler PSSD improved the drainage of excess water and salts from the root zone, thus increasing the grain/seed test weight and finally the yield of both crops (Figure 7). Therefore, this study illustrated the efficiency of rice residue-filled cut-soiler PSSD in mitigating the negative effect of increased irrigation water salinity on soil salinization and the consequent adverse impact on various growth and yield parameters in pearl millet and mustard.

5 Conclusions

The rice residue-filled cut-soiler-constructed preferential shallow sub-surface drainage system removed excess salts from the root zone with percolating water, especially during the rainy season. Continued leaching of the salt from the layer above the cut-soiler line maintained a lower salinity in the soil profile with improved soil moisture conditions for plant growth even under saline water irrigation. Furthermore, it increased dry matter accumulation, net assimilation rate, CGR, RGR, leaf area, and LAI, as well as the production of both pearl millet and mustard crops in saline semi-arid conditions. This study demonstrated the effectiveness of rice residue-filled cut-soiler PSSD in reducing the salinity of the soil profile and preventing salt accumulation under saline water irrigation. This study also showed its agronomic potential to mitigate root zone salinity to improve the productivity of pearl millet and mustard crops in saline groundwater or saline irrigation agroecologies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

N: Data curation, Formal analysis, Methodology, Validation, Writing – original draft. GY: Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Conceptualization, Funding acquisition, Project administration, Supervision, Visualization, Writing – review & editing. RY: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. AK: Investigation, Methodology, Writing – review & editing. AR: Investigation, Methodology, Writing – review & editing. GP: Methodology, Writing – review & editing. SK: Investigation, Writing – review & editing. BN: Investigation, Methodology, Writing – review & editing. JO: Conceptualization, Investigation, Methodology, Writing – review & editing. KO: Conceptualization, Funding acquisition, Writing – review & editing. SC: Conceptualization, Supervision, Writing – review & editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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