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Salt Removal through Residue-Filled Cut-Soiler Simulated Preferential Shallow Subsurface Drainage Improves Yield, Quality and Plant Water Relations of Mustard (*Brassica juncea* L.)

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Abstract: Soil salinity and the use of saline groundwater are two major constraints in crop production, which covers a ~1.0 billion ha area of arid and semi-arid regions. The improved drainage function of soil can modify the salty growing environment for higher agricultural production. The present study evaluated the effectiveness of cut-soiler-constructed rice residue-filled preferential shallow subsurface drainage (PSSD) to improve the drainage function and its effect on the yield, quality and plant–water relations of mustard over 2019–2021. Cut-soiler-simulated drains were made in a semi-controlled lysimeter (2 × 2 × 3; L*W*H m) as the main plot treatment in a double replicated split–split experiment with two soil types (subplot) and three irrigation water salinities (4, 8 and 12 dS m^{-1}) as the sub-sub-plot treatment. The drainage volume of variable salinity (EC), dependent on the total water input, was substantially higher in the rainy season (April to October), i.e., 16.6, 7.76 and 12.0% during 2018, 2019 and 2020, with 1.7, 0.32 and 0.77 kg salt removal per lysimeter, compared to the post-rainy season. The mustard seed, straw and biological yields were improved by 31.4, 14.41 and 18.08%, respectively, due to a positive effect on plant–water relations. The mustard seeds produced in the cut-soiler-treated plots recorded higher oil, crude fiber and protein contents and a lower erucic acid content. The increase in salt load, by higher-salinity irrigation water, was also efficiently managed by using cut-soiler PSSD. It was found that the saline irrigation water up to 12.0 dS m^{-1} can be used under such PSSD without any extra salt loading. The present study showed the potential of cut-soiler PSSD in root zone salinity management by improving drainage in salt-affected arid regions.

Keywords: cut-soiler; mustard (*Brassica juncea* (L.)); PSSD; salinity

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1. Introduction

The land and water resources of arid and semi-arid regions are limited and their degradation further hampers agricultural production in these regions. The optimum utilization of these resources is essential for sustainable agricultural production and to feed the burgeoning population, which is expected to increase to around 9.25 billion by 2050 [1]. Salinity is a severe soil degradation problem and a major constraint in crop production, which covers a ~1 billion ha area of arid and semi-arid regions. Out of all the salt-affected areas worldwide, ~397 million hectares (M ha) is saline, constituting 20% of total cultivated land and 50% of the irrigated areas of Earth [2]. In India, around 2.1% of the total geographical area, around 6.73 M ha, is salt affected, of which 2.95 M ha is saline, covering 16 states and two Union Territories [3]. This salt-affected area is estimated to increase to about 16.2 M ha by 2050 [4]. Further, 32 M ha, i.e., 2%, of the total 1500 M ha dryland agriculture in this country is affected by varying degrees of secondary salinization. Such a severity and extent of salinity hinder the growth and productivity of crop plants to variable extents [5] and result in annual losses of 16.84 mt of farm production, valued at ~USD 3.06 billion in India alone [6,7]. The losses are likely to increase manifold, with projected increases in salt-affected soils rising to 16.2 M ha by 2050 [8]. In addition to the regular seasonal environmental constraints, field crops are often subjected to periods of soil and atmospheric water deficits during their life cycles as well as to high soil/water salinity in arid and semi-arid regions, including many parts of India. These limitations are likely to increase in the future climatic scenarios, due to the uneven distribution or a decrease in the amount of effective precipitation and increase in evapotranspiration [9,10].

An area of about 5.5 M ha also suffers from waterlogging in this country [11]. The post-Green Revolution needs of increased irrigation, especially in low and erratic rainfall areas, have caused the overuse of canal and groundwater irrigation resources [12]. Most of the canal-irrigated and underlain saline groundwater irrigated areas of Haryana State face the problems of a rising water table and salinization [13,14]. The estimated saline and waterlogged areas of this state are about 49,157 ha and 500,000 ha, respectively, which creates hydrological imbalances [15]. Canal irrigation system seepages and limited saline groundwater use are the other factors aggravating this problem. Low-quality groundwater ranges between 32 and 84% of the total groundwater resources used for irrigation in different states of India [16].

Salt-stress-induced crop losses are likely to increase substantially in the coming decades if appropriate corrective measures are not undertaken to tackle the intertwined menaces of salinity, waterlogging and ions toxicities. Therefore, to sustain the agricultural productivity of these degraded lands, and to prevent further salinization arising due to irrigation with underlying saline groundwater in the arid regions, there is need for cost-effective salinity management techniques. Despite all of this research, development efforts and schemes, the problem of salinity, especially in poorly drained soils, is increasing. An 'on farm technology' solution that can be adopted at the individual farm/farmer level is required to solve this. Salinity undermines soil quality, which restricts plant growth and productivity. The growth response of different plants to salinity is different [17]. Therefore, soil salinity often restricts options for cropping in a given area. Choosing more adaptable crops and salt-tolerant varieties is the plant-system-side approach to tackle salinity, especially dryland saline conditions. Indian mustard (*Brassica juncea* L. Czern and Coss), grown in more than 50 countries across the globe, is an important oil-seed crop across the world. This crop often encounters salinity and drought stress during its growing period, as it is grown extensively in arid and semi-arid regions of the world. The stresses due to the salinity of soil and water contribute to greater yield losses (both seed and oil yields) [18]. Globally, India accounts for 19.29 and 11.27% of the total area and production, respectively, of mustard [19].

The approaches used for the management of salinity and sustainable crop production, in a salt-affected environment, can be grouped into two categories, viz., the modification of the growing environment to suit the desired crop plants and making improvements to the plant system to tolerate salt stress.

To modify the salty growing environment, the provision of the drainage function has been used more extensively. This helps to maintain more favorable moisture and salt regimes in the root zone, which lead to improvements in soil properties and ultimately to higher crop productivity [20,21]. The present study evaluated the effectiveness of a novel technique, i.e., cut-soiler-constructed preferential shallow subsurface drainage (PSSD) to improve the drainage function of soil layers. A cut-soiler is a tractor-mounted farm implement that uses and manages the surface lying material, viz., residue, scattered straw, or remaining stems for making residue-filled subsurface drains while running on the field. Cut-soiler PSSD has been found to be effective in the management of surface waterlogged rice fields of Japan and tested in other parts of the world. The improved drainage seen when using a cut-soiler could make it a remunerative alternative for the management of dry land, salt-affected soils in India for sustainable crop production. Keeping the above aspects in view, this study evaluated the effect of cut-soiler-based salinity management on salt and water dynamics and the subsequent improvements in growth, physiology, yield and quality of mustard in semi-arid saline regions.

2. Materials and Methods

2.1. Experimental Site

The experimental site is located at Karnal (29°42′ N latitude and 76°57′ E longitude, with an altitude of 243 m above mean sea level) in North Western Indo-Gangetic Plain Zone of Haryana state. This site has a semi-arid, subtropical, monsoonal climate. This zone receives rainfall from both south-west and north-east monsoons. Karnal faces extremes of both high and low temperatures. During summer, the maximum temperature goes up to 45 °C, and in winter the minimum temperature reaches near freezing point. The hottest months are May and June, with the mean maximum temperature ranging from 32.7 to 42.8 °C, whereas the mean minimum temperature of the coolest months (December and January) falls in the range of 3.4 to 10.8 °C. The average annual rainfall of the site is about 757.6 mm [22], while the annual rainfall, evapotranspiration and annual aridity indexes of 2019–2020 and 2020–2021 were 117 and 589.6 mm, 481.3 and 513.2 mm, and 0.18 and 0.40%, respectively. The seasonal temperature, rainfall and evaporation are provided in Figures 1 and 2. The initial soil physico-chemical properties of two soil types are presented in Table 1. The irrigation waters of different salinities were prepared by the mixing of saline water collected from the representative saline groundwater site and tap water. The final EC values of the three types of saline water were 4.13, 8.10 and 12.05 dS m^{-1}.

Table 1. Initial physico-chemical properties of the experimental soil.

Soil Properties	ECe [1] (dS m^{-1})	pHs [2]	Bulk Density	Hydraulic Conductivity (cm Day^{-1})	Texture	Soil Moisture	
						Before Sowing (%)	After Harvest (%)
Saline soil	6.0	7.14	1.57	30–51	Sandy loam	20.55	18.46
Heavy-textured soil	3.02	7.34	1.67	8–13	Silty clay loam	23.36	19.21

[1] ECe: EC of aqueous soil saturation extract; [2] pHs: pH of aqueous soil saturation paste.

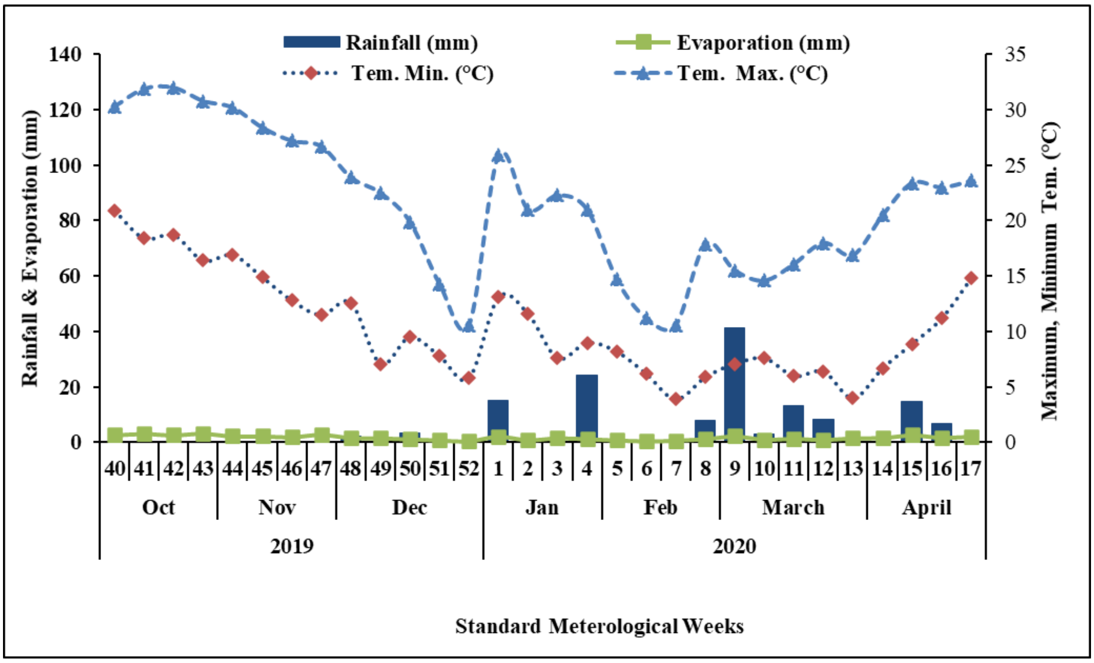

Figure 1. Average weekly weather during 2019–2020 (RF—rainfall; Temp. Max.—maximum temperature; Temp. Min.—minimum temperature).

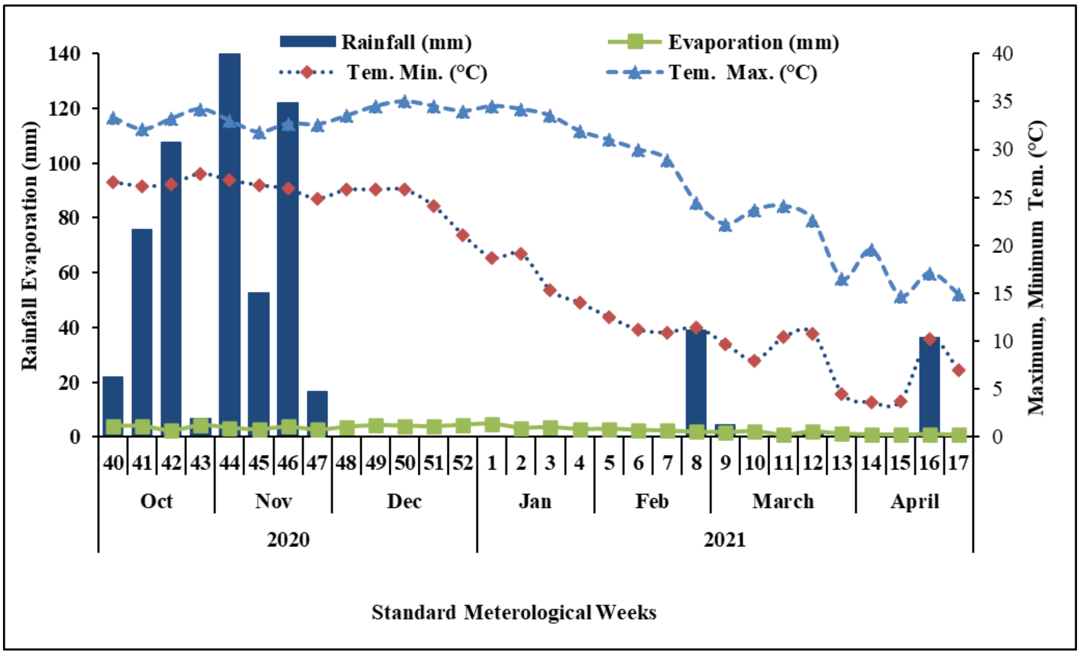

Figure 2. Average weekly weather during 2020–2021 (RF—rainfall; Temp. Max.—maximum temperature; Temp. Min.—minimum temperature).

2.2. Experimental Details

The study was conducted over 2019–2021 at the ICAR-CSSRI semi-controlled lysimeter facility (each lysimeter plot is 2 m × 2 m × 3 m (L*W*H)), located at Karnal. A double split plot design experiment with two replications comprised 12 treatment combinations. Rice residue-filled cut-soiler-simulated preferential drainage was applied in 12 plots as the main plot treatment along with the control (without the cut-soiler), in another 12 plots. The two soil types in the subplots, i.e., sandy loam saline soil and heavy-textured soil, were collected from selected representative sites as the subplot treatment, i.e., 6 plots of each type of soil in both cut-soiler and control conditions. Three saline water irrigation treatments, viz., 4, 8 and 12 decisiemens per meter (dS m^{-1}) were applied in sub-sub-plots and scheduled as per crop water requirements. The residue-filled V shape drains (L (2.0 m) × W (15 cm top; 10 cm bottom) × H (10 cm)) were constructed manually at 60 cm below the surface (by filling rice residue @ 6 Mg ha^{-1}) to simulate the effect of cut-soiler preferential drainage in the field in July 2018. The nylon and gravel filter materials were used at the drain outlet connecting point to avoid clogging. The mustard (Var. CS-58) was sown on 02 November 2019 and 23 October 2020 (Winter; Rabi season), respectively. All the recommended practices for the cultivation of mustard in the area were followed.

2.3. Sampling and Measurements

Three irrigations of 5 cm each (including pre-sowing irrigation) of variable designated salinities (made by mixing natural saline water with good-quality tap water) were applied in both seasons. The leachate drained from the cut-soiler outlet was collected and measured continuously to estimate the total drainage volume. The salt removal was calculated on the basis of the total volume of drainage and salinity of the leachate collected [23]. The soil salinity (EC_e) under different treatments was measured as per the method prescribed by Richards [24] and soil moisture content was determined on the basis of the oven dry weight by using the gravimetric method [6] at the beginning and end of each growing season. The mustard crop performance was assessed in terms of seed, straw and biological yields (Mg ha^{-1}) under different treatments. The seed analysis for oil, protein, erucic acid and crude fiber content was performed using a pre-standardized Fourier Transform Near Infrared Reflectance Spectrometer (FT-NIR, Perkin Elmer, Waltham, MA, USA). Plant–water relations, i.e., relative water content (RWC%) water potential (-MPa), osmotic potential (-MPa) and turgor potential (-MPa) [25], at vegetative and reproductive stages were measured; the leaf samples of selected plants were collected from each plot between 9:00 and 10:00 AM and sealed in humified polythene bags at a low temperature, using standard procedures.

2.4. Statistical Analysis

All the data were subjected to statistical analysis using SAS Version 9.3 [26]. The pairwise means were compared using Least Significant Difference (LSD) test. A correlation analysis was performed to determine the association between the traits using the Pearson coefficient procedure.

3. Results

3.1. Changes in Soil Salinity

Data on the soil EC_e of experimental lysimeter plots are presented in Figure 3. Comparing the two study years, the salinity was significantly higher in the year 2019–2020 than 2020–2021 before sowing and after the harvest of mustard crops at all soil depths. The salinity in surface soil layers (0–15 and 15–30 cm) consistently remained higher after the harvesting of mustard crop as compared to before the sowing of mustard crop for both the years (2019–2020 and 2020–2021). The soil salinity was found to be the lowest in the upper soil layer (0–15 cm), and increased with depth at the time of sowing (in October) across the cut-soiler, soil type and saline irrigation water treatments (Figure 3). However, after harvest soil sampling in both seasons, the soil salinity was the highest in the upper layer (0–15 cm) and decreased with depth. The EC_e was significantly lower in the cut-soiler plots at all four sampled soil depths in comparison to the condition without cut-soiler plots at all sampling occasions. Under the cut-soiler treatment, the EC_e values before sowing the mustard at 0–15, 15–30, 30–60 and 60–90 cm depths were 37.78, 40.06, 39.22 and 37.24% lower than without cut-soiler treatment. Similarly, the EC_e values after mustard harvest at 0–15, 15–30, 30–60 and 60–90 cm depths were 37.74, 42.86, 46.19 and 57.07% lower in cut-soiler plots than control ones.

The EC_e of soil at all depths was significantly higher in sandy loam saline soil than heavy-texture soil at the sowing and harvest stages of mustard crop in both seasons. The EC_e values at 0–15, 15–30, 30–60 and 60–90 cm depths before the sowing of mustard were 3.15, 3.69, 4.20 and 4.57 dS m^{-1}, respectively, in comparison to the corresponding magnitude in heavy-textured soil (1.10, 1.31, 1.54 and 1.81 dS m^{-1}). The EC_e values after the harvest of mustard crop in the respective soil layers in sandy loam saline soil were 5.65, 5.18, 4.78 and 4.03 dS m^{-1} and the corresponding EC_e values in heavy-texture soil were 2.82, 2.52, 2.28 and 1.83 dS m^{-1}.

While comparing different salinity levels of irrigation water, it was observed that irrigation water salinity had a significant effect on the EC_e of soil consistently in each sample. At the sowing stage in October, with the application of 8 dS m^{-1}, the EC_{iw} values were 18.54, 11.52, 10.12 and 7.91% higher than the EC_e values with 4 dS m^{-1}, recorded at at 0–15, 15–30, 30–60 and 60–90 cm depths, respectively. The increases in soil salinity with the application of 12 dS m^{-1} EC_{iw} were 39.33, 34.10, 38.46 and 36.33% at the respective soil depths. After mustard harvest (April), the increases in soil EC_e at 8 dS m^{-1} were 16.76, 22.88, 23.29 and 20.90% at 0–15, 15–30, 30–60 and 60–90 cm depths, respectively, over 4 dS m^{-1} EC_{iw}. The respective increases with the application of 12 dS m^{-1} EC_{iw} were 32.42, 39.18, 39.38 and 39.34% at 4 dS m^{-1} EC_{iw}.

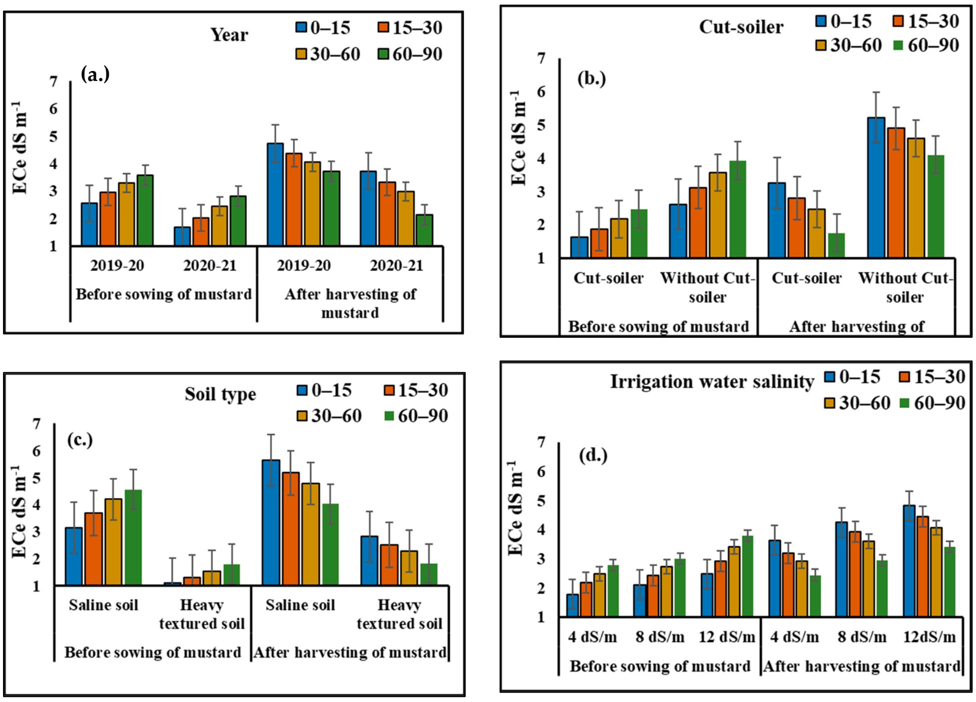

Figure 3. Changes in soil salinity (ECe) at different soil depths due to study year (**a**); cut-soiler (**b**); soil type (**c**); saline irrigation water; (**d**) application at before sowing and after harvest of mustard.

3.2. Soil Moisture Content (%)

The moisture content (%) was significantly higher in year 2020–2021 than 2019–2020 before sowing and after the harvest of mustard crop (Figure 4). The moisture content was found to be lower before sowing (18.17%) and after the harvest of mustard (12.96%), under the cut-soiler as opposed to without cut-soiler treatment. The soil moisture content was significantly higher in heavy-textured soil than sandy loam saline soil. The soil moisture content values before sowing and after the harvest of mustard crop were 17.92 and 12.75% and the corresponding soil moisture content values in heavy-textured soil were 19.95 and 14.76%.

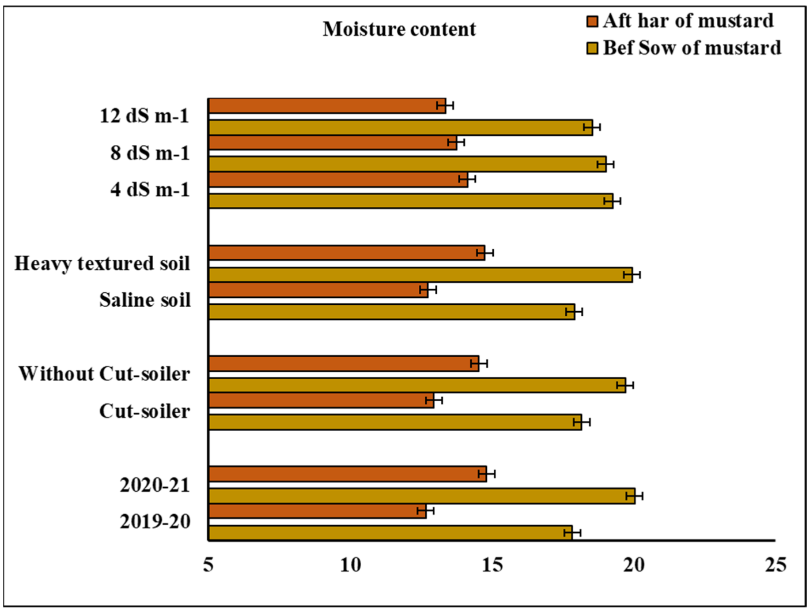

Figure 4. Effect of cut-soiler, soil type, irrigation water salinity and year on soil moisture content (%) before sowing and after the harvest of mustard.

Comparing different salinity levels of irrigation water, it was observed that before sowing and after the harvest of mustard, there was no significant change in soil moisture content with the application of 4, 8 and 12 dS m^{-1} EC$_{iw}$

3.3. Mass Balance of Drained Water and Salt

The water drained from the cut-soiler PSSD in different growing seasons was monitored, salt and the water balance calculated on the basis of rainfall, irrigation applied and the volume and salinity of drained water (Table 2). In the first season, i.e., from 18 June to 18 October, on average approximately 188 mm water was drained out from cut-soiler PSSD, which was 16.6% of the total volume of the water input (irrigation + rainfall). The salinity of drained water was 3.5 dS m^{-1} and the average salt removal per lysimeter was recorded at about 1.7 kg lysi^{-1}. There was no drained water from 18 November to 19 April, but ~42.7 mm water drained out from cut-soiler PSSD in the subsequent season from 19 May to 19 October, which was about 7.76% of the water input with 2.93 dS m^{-1} salinity and the estimated drained salt load was about 0.32 kg lysi^{-1}. From 19 November to 20 April, again very scanty drainage (14.6 mm) was recorded, i.e., 3.09% of the total water input, but with a higher salinity of 3.14 dS m^{-1} and the drained salt was about 0.12 kg lysi^{-1}. The drainage water from 20 May to 20 October was 137.5 mm (12.0% of the total water input) with 2.16 dS m^{-1} salinity, which led to 0.77 kg lysi^{-1} salt removal. However, there was no drainage and thus no salt removal from 20 November to 21 April (Table 2).

Table 2. Soil water and salt balance components at different times.

Period	Rainfall (mm)	Irrigation (mm)	Evaporation (mm)	Drain Water (mm)	Drain EC * (dS m^{-1})	Salt Removed (kg/lys *)
18 June to 18 October	984.7	3 × 50	524.1	188.4 (753 L)	3.50	1.7
18 November to 19 April	79.6	3 × 50	491.9	–	–	–
19 May to 19 October	400.3	3 × 50	984.8	42.7 (170 L)	2.93	0.32
19 November to 20 April	322.3	3 × 50	444.4	14.6 (58.4 L)	3.14	0.12
20 May to 20 October	995.3	3 × 50	873.0	137.5 (550 L)	2.16	0.77
20 November to 21 April	113.0	3 × 50	542.1	—	–	

* EC—electrical conductivity; lys—lysimeter.

3.4. Yields (t ha^{-1})

The seed (2.51 t ha^{-1}), straw (8.60 t ha^{-1}) and biological (11.11 t ha^{-1}) yields of mustard were significantly higher in 2020–2021 as compared to 2019–2020 (Table 3). The cut-soiler treatment significantly increased mustard seed (2.80 t ha^{-1}), straw (8.89 t ha^{-1}) and biological (11.69 t ha^{-1}) yields in comparison to treatment without the cut-soiler (2.13, 7.77 and 9.90 t ha^{-1}, respectively). The seed, straw and biological yields were 31.5, 14.41 and 18.08% higher under cut-soiler treatments compared to control treatments. The cut-soiler treatment produced a higher HI (23.90%) than without a cut-soiler (21.49%).

The average seed, straw and biological yields under light-texture saline soil were 2.34, 8.10 and 10.44 t ha^{-1}, which were 09.65, 05.26 and 06.36% lower than the corresponding values recorded for heavy-texture soil (2.59, 8.55 and 11.15 t ha^{-1}, respectively). Similarly, the HI in light-texture saline soil was significantly lower (22.25%) than heavy-texture soils (23.14%).

The effect of saline irrigation water treatments was also found significant, where the mustard seed yield declined from 2.64 to 2.46 t ha^{-1} (6.82%) and then further to 2.29 t ha^{-1} (13.26%) from 4 to 8 and 12 dS m^{-1} salinity of applied irrigation water, respectively. There was 3.7% decrease in straw yield with increase in salinity of applied irrigation from 4 dS m^{-1} (8.64 t ha^{-1}) to 8 dS m^{-1} (8.32 t ha^{-1}) and further to 7.29% with increase in EC$_{iw}$ to 12 dS m^{-1} (8.01 t ha^{-1}). This decline in biological yield was 4.52% and 8.77% with increase in EC$_{iw}$ from 4 dS m^{-1} to 8 and further to 12 dS m^{-1}. The significant decrease in HI was also recorded with increased salinity of applied irrigation water from 4 dS m^{-1} (23.29%) to 8 dS m^{-1} (22.69%) and further to 12 dS m^{-1} in 22.11%.

Table 3. Effect of study year, cut-soiler, soil type and irrigation water salinity on yield attributes of mustard. A, B and C superscripted with values described the significant differences in given values on the basis of critical differences.

Treatments/Traits	Seed Yield ($t\ ha^{-1}$)	Straw Yield ($t\ ha^{-1}$)	Biological Yield ($t\ ha^{-1}$)	Harvest Index (%)
		Years		
2019–2020	2.41 ^{B}	8.06 ^{B}	10.47 ^{B}	22.90 ^{A}
2020–2021	2.51 ^{A}	8.60 ^{A}	11.11 ^{A}	22.50 ^{B}
CD (p = 0.05)	0.06 ± 0.02	0.15 ± 0.05	0.21 ± 0.06	0.27 ± 0.08
		Cut-soiler		
Cut-soiler	2.80 ^{A}	8.89 ^{A}	11.69 ^{A}	23.90 ^{A}
Without cut-soiler	2.13 ^{B}	7.77 ^{B}	9.90 ^{B}	21.49 ^{B}
CD (p = 0.05)	0.06 ± 0.02	0.15 ± 0.05	0.21 ± 0.06	0.27 ± 0.08
		Soil type		
Saline soil	2.34 ^{B}	8.10 ^{B}	10.44 ^{B}	22.25 ^{B}
Heavy-textured soil	2.59 ^{A}	8.55 ^{A}	11.15 ^{A}	23.14 ^{A}
CD (p = 0.05)	0.03 ± 0.01	0.07 ± 0.03	0.08 ± 0.04	0.21 ± 0.1
		Irrigation water salinity		
S1 (4 $dS\ m^{-1}$)	2.64 ^{A}	8.64 ^{A}	11.29 ^{A}	23.29 ^{A}
S2 (8 $dS\ m^{-1}$)	2.46 ^{B}	8.32 ^{B}	10.78 ^{B}	22.69 ^{B}
S3 (12 $dS\ m^{-1}$)	2.29 ^{C}	8.01 ^{C}	10.30 ^{C}	22.11 ^{C}
CD (p = 0.05)	0.03 ± 0.02	0.08 ± 0.04	0.1 ± 0.05	0.26 ± 0.12

The significant interaction effects of soil type and irrigation water salinity (p = 0.0005), cut-soiler and soil type (p = 0.0001) and cut-soiler and irrigation water salinity ($p \leq 0.0001$) on seed yield were recorded (Figure 5). The seed yield was the highest (3.24 $t\ ha^{-1}$) under cut-soiler with heavy soil and 4 $dS\ m^{-1}$ EC_{iw} in the year 2020–2021 and lowest (1.79 $t\ ha^{-1}$) in the treatment without a cut soiler, saline soil with 12 $dS\ m^{-1}$ EC_{iw} in 2019–2020. The highest biological yield (13.17 $t\ ha^{-1}$) was recorded for the treatment with the cut-soiler, heavy-textured soil and an irrigation water salinity of 4 $dS\ m^{-1}$ in 2020–2021 and the lowest biological yield (8.65 $t\ ha^{-1}$) was found in the treatment without the cut-soiler, with saline soil and an irrigation water salinity of 12 $dS\ m^{-1}$ in the previous year.

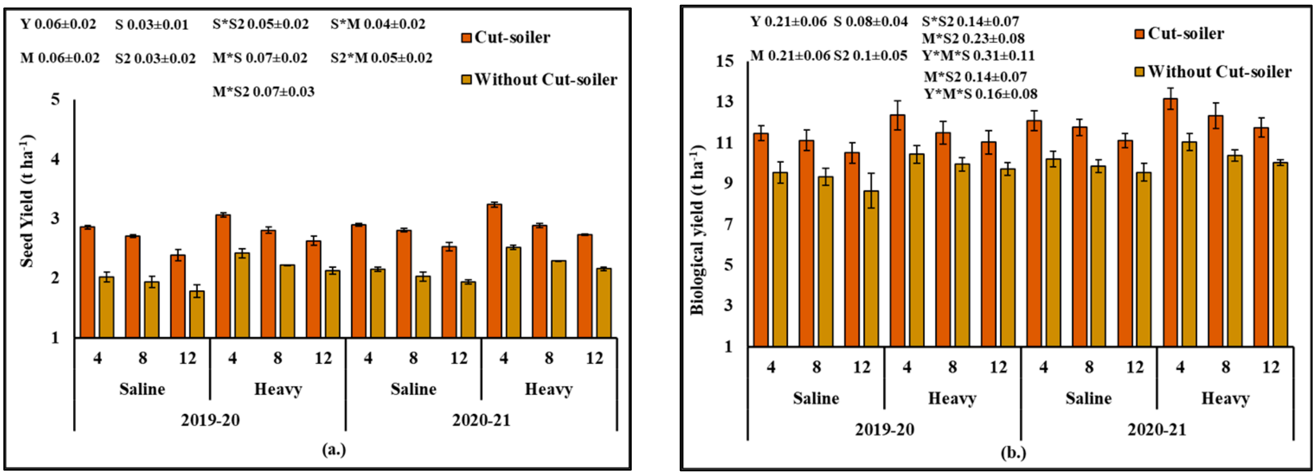

Figure 5. Interaction effect of study year × cut-soiler × soil type × irrigation water salinity on seed yield (**a**) and biological yield (**b**) of mustard crop.

3.5. Quality Parameters

The oil (39.47%) and protein (19.59%) contents were higher in the year 2020–2021 as compared to 2019–2020 (38.99; 19.42%). The erucic acid content was found to be lower (39.66%) in seeds harvested in 2020–2021 as compared to in 2019–2020 (40.87%), but there was no difference in crude fiber content (Table 4). The cut-soiler treatment produced significantly higher oil (39.53%), crude fiber (10.39%) and protein (19.75%) contents as compared to treatment without the cut-soiler (38.92; 09.53 and 19.26%). The erucic acid content in seeds produced under the cut-soiler treatment was found to be lower (38.79%) than treatment without the cut-soiler (41.74%).

The mustard seed oil (39.39%), crude fiber (10.27%) and protein contents (19.69%) were higher in heavy-texture soil than lighter-texture saline soil (39.06; 9.65 and 19.32%). Heavy-texture soils produced seeds with lower (37.22%) erucic acid contents as compared to saline soils (43.31%). The oil, protein and crude fiber contents (%) were decreased significantly with an increase in irrigation water salinity level, from 4 dS m^{-1} (39.40, 10.15 and 19.63%) to 8 dS m^{-1} (39.20, 9.94 and 19.51%) and then further to 12 dS m^{-1} (39.08, 9.79 and 19.38%). The erucic acid contents increased significantly with an increase in the level of salinity from 39.00% in EC_{iw} 4 dS m^{-1} to 40.24% in EC_{iw} 8 dS m^{-1}, and further to 41.56% in EC_{iw} 12 dS m^{-1}.

Table 4. Oil content, crude fiber, protein content and erucic acid in mustard seed, as influenced by study year, cut-soiler, soil type and irrigation water salinity. A, B and C superscripted with values described the significant differences in given values on the basis of critical differences.

Treatments/Traits	Oil Content (%)	Crude Fiber (%)	Protein Content (%)	Erucic Acid (%)
		Years		
2019–2020	38.99 ^{B}	9.87	19.42 ^{B}	40.87 ^{A}
2020–2021	39.47 ^{A}	10.05	19.59 ^{A}	39.66 ^{B}
CD (p = 0.05)	0.12 ± 0.04	NS	0.11 ± 0.03	0.21 ± 0.07
		Cut-soiler		
Cut-soiler	39.53 ^{A}	10.39 ^{A}	19.75 ^{A}	38.79 ^{B}
Without cut-soiler	38.92 ^{B}	9.53 ^{B}	19.26 ^{B}	41.74 ^{A}
CD (p = 0.05)	0.12 ± 0.04	0.2 ± 0.06	0.11 ± 0.03	0.21 ± 0.07
		Soil type		
Saline soil	39.06 ^{B}	9.65 ^{B}	19.32 ^{B}	43.31 ^{A}
Heavy-textured soil	39.39 ^{A}	10.27 ^{A}	19.69 ^{A}	37.22 ^{B}
CD (p = 0.05)	0.1 ± 0.05	0.07 ± 0.03	0.05 ± 0.02	0.36 ± 0.17
		Irrigation water salinity		
S1 (4 dS m^{-1})	39.40 ^{A}	10.15 ^{A}	19.63 ^{A}	39.00 ^{C}
S2 (8 dS m^{-1})	39.20 ^{B}	9.94 ^{B}	19.51 ^{B}	40.24 ^{B}
S3 (12 dS m^{-1})	39.08 ^{C}	9.79 ^{C}	19.38 ^{C}	41.56 ^{A}
CD (p = 0.05)	0.12 ± 0.06	0.08 ± 0.04	0.06 ± 0.03	0.44 ± 0.21

The multiple interaction effects of the cut-soiler, soil type and irrigation water salinity on crude fiber, protein and erucic acid contents were found to be significant (Figure 6). The highest oil content (40.74%), crude fiber percentage (11.53%) and protein content (20.50%) were observed in the treatment with the cut-soiler, heavy-textured soil and an irrigation water salinity of 4 dS m^{-1}, and the lowest oil content (38.58%), crude fiber (9.17%) and protein content (18.97%) were observed in the treatment without a cut-soiler, with saline soil and an irrigation water salinity of 12 dS m^{-1}. The erucic acid content was the highest (47.26%) in the treatment without the cut-soiler and with saline soil at an irrigation water salinity of 12 dS m^{-1} and the lowest erucic acid content (33.1%) was recorded in the treatment with the cut-soiler in heavy-texture soil and an irrigation water salinity of 4 dS m^{-1}.

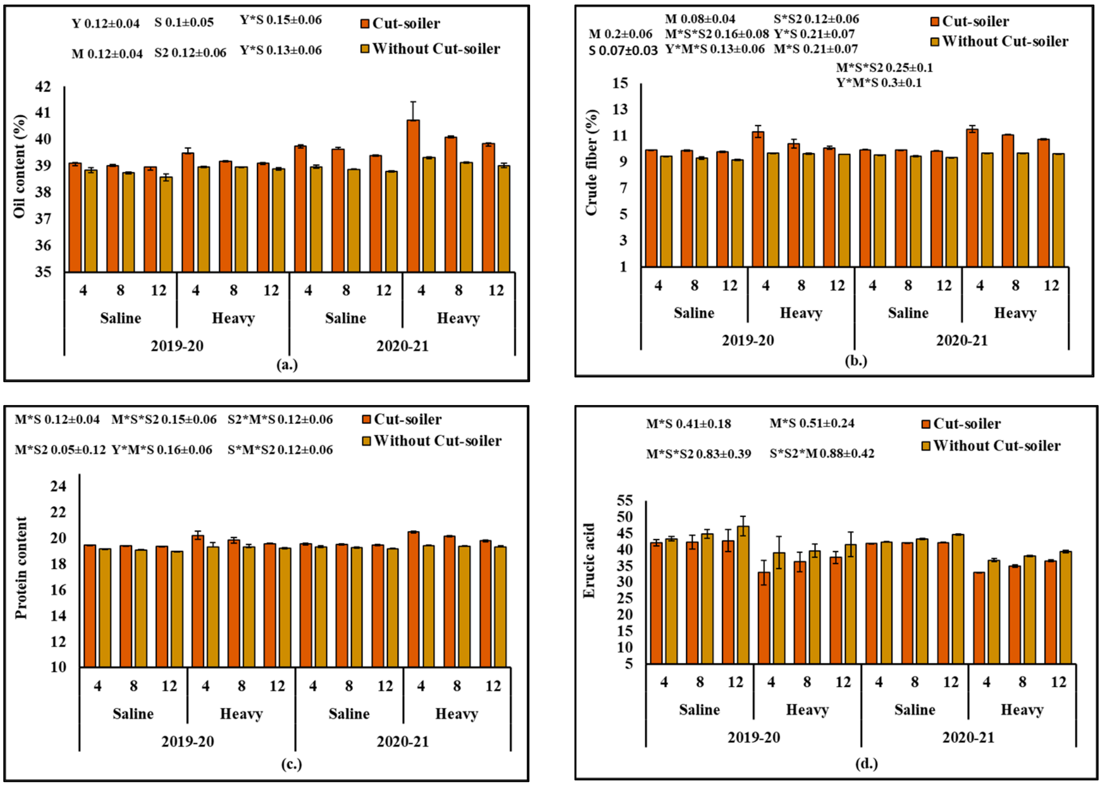

Figure 6. Interaction effect of study year × cut-soiler × soil type × irrigation water salinity on oil content (**a**); crude fiber (**b**); protein content; (**c**) and erucic acid (**d**) of mustard crop.

3.6. Plant Water Relations

All plant–water relation parameters were significantly influenced by the study year, except relative water content at the vegetative stage and turgor pressure at both vegetative and reproductive stages. Mustard maintained a higher RWC at the reproductive stage and higher (less negative values) water potential (ψw) and osmotic potential (ψs) at both stages over 2020–2021 compared to 2019–2020 (Table 5). The RWC under the cut-soiler treatment was higher at the vegetative (91.26%) and reproductive (82.75%) stages than that of the treatment without the cut-soiler (81.48; 74.17%). The cut-soiler caused 28.72 and 22.44% improvements in ψw, and 15.15 and 18.69% improvements in ψs at the vegetative and reproductive stages. ψp under the cut-soiler treatment was higher at the vegetative (0.430 MPa) stage only. Soil type also significantly affected these traits. A lower RWC (83.61 and 76.12%) was recorded in light-textured saline soil as compared to heavy-textured soil (89.13 and 80.81%). The water potential and osmotic potential were found to be higher (less negative values) in heavy-textured soil planted crop, i.e., 1.71 and −1.40 MPa ψw and −2.12 and −1.99 MPa ψs, respectively, in comparison to saline soil (−2.59, −1.86 MPa ψw and −2.84, −2.68 MPa ψs). The turgor potential was higher in heavy-textured soil at the vegetative stage (0.410) and lower at the reproductive stage (0.592) than light-textured saline soil. Increasing the salinity of irrigation water significantly reduced RWC, ψw, ψs and ψp at both the vegetative and reproductive stages. The maximum reductions of 4.3 and 4.24% were observed at the respective stages in 12 dS m^{-1} EC_{iw} as compared to EC_{iw} ~4 dS m^{-1}. Increasing the irrigation water salinity resulted in more negative ψw, ψs and ψp at the vegetative (−1.90, −2.12 and −2.43 MPa ψw; −2.12, −2.46 and −2.86 MPa ψs; and 0.23, 0.341 and 0.43 MPa ψp) and reproductive (−1.27, −1.62 and −2.01 MPa ψw; −1.97, −2.32 and −2.72 MPa ψs; and 0.719, 0.715 and 0.711 MPa ψp) stages at EC_{iw}~4, 8 and 12 dS m^{-1}, respectively.

Table 5. Relative water content (RWC), Water potential (WP), Osmotic potential (OP) and Turgor pressure (TP) in mustard seed as influenced by study year, cut-soiler, soil type and irrigation water salinity. A, B and C superscripted with values described the significant differences in given values on the basis of critical differences.

Treatments/ Traits	Relative Water Content (%)		Water Potential (−MPa)		Osmotic Potential (−MPa)		Turgor Pressure	
	Veg	Repro	Veg	Repro	Veg	Repro	Veg	Repro
Years								
2019–2020	86.14	77.82 B	−2.27 A	−1.71 A	−2.57 A	−2.42 A	0.301	0.710
2020–2021	86.59	79.11 A	−2.03 B	−1.55 B	−2.39 B	−2.26 B	0.360	0.700
CD (p = 0.05)	NS	0.5 ± 0.2	0.09 ± 0.04	0.06 ± 0.02	0.16 ± 0.06	0.15 ± 0.06	NS	NS
Cut-soiler								
Cut-soiler	91.26 A	82.75 A	−1.88 B	−1.47 B	−2.31 B	−2.14 B	0.430 A	0.670
Without cut-soiler	81.48 B	74.17 B	−2.42 A	−1.80 A	−2.66 A	−2.54 A	0.232 B	0.742
CD (p = 0.05)	0.62 ± 0.25	0.5 ± 0.2	0.09 ± 0.04	0.06 ± 0.02	0.16 ± 0.06	0.15 ± 0.06	0.1 ± 0.04	NS
Soil type								
Saline soil	83.61 B	76.12 B	−2.59 A	−1.86 A	−2.84 A	−2.68 A	0.251 B	0.821 A
Heavy-textured soil	89.13 A	80.81 A	−1.71 B	−1.40 B	−2.12 B	−1.99 B	0.410 A	0.592 B
CD (p = 0.05)	0.37 ± 0.18	0.42 ± 0.21	0.06 ± 0.03	0.06 ± 0.03	0.1 ± 0.05	0.13 ± 0.06	0.11 ± 0.05	0.13 ± 0.07
Irrigation water salinity								
S_1 (4 dS m^{-1})	88.30 A	80.55 A	−1.90 C	−1.27 C	−2.12 C	−1.97 C	0.230 B	0.719
S_2 (8 dS m^{-1})	86.81 B	78.54 B	−2.12 B	−1.62 B	−2.46 B	−2.32 B	0.341 AB	0.715
S_3 (12 dS m^{-1})	84.00 C	76.31 C	−2.43 A	−2.01 A	−2.86 A	−2.72 A	0.430 A	0.711
CD (p = 0.05)	0.45 ± 0.22	0.51 ± 0.25	0.08 ± 0.04	0.08 ± 0.04	0.12 ± 0.06	0.16 ± 0.08	0.13 ± 0.07	NS

3.7. Relations of Yields with Plant Water Relations and Physiological Traits

The effects of the plant physiological attributes on grain and biological yields were determined by performing a principal component analysis (PCA) (Figure 7). The first two principal components (PC1: 74.60% and PC2: 11.78%) accounted for nearly 86% of the cumulative variation. Treatments with 4 dS m^{-1} irrigation water salinity were clustered in the first quadrant. Erucic acid and grain yield showed a unique separation and lay in opposite quadrants in the PCA biplot. GY, along with RWC, SY, BY, HI, OC, OC and PC, laid in one quadrant, while erucic acid and water potential (OP, WP and TP) lay the opposite quadrant.

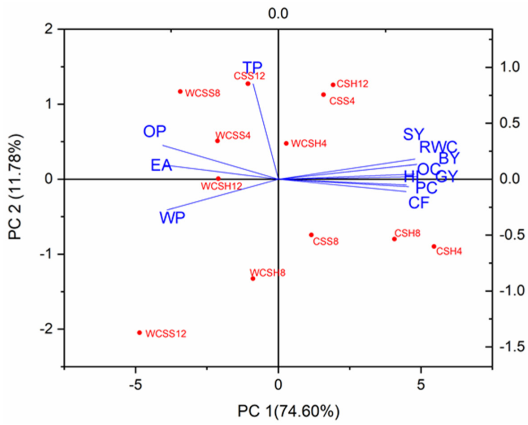

Figure 7. Biplot showing variable loadings for the first two principal components on mustard grain (GY), straw (SY), biological (BY) yields and harvest index (HI), as well as plant–water relations. RWC, relative water content; WP, water potential; OP, osmotic potential; TP, turgor potential. Quality parameters are oil content (OC), crude fiber (CF), protein content (PC) and erucic acid content (EC).

A strong positive interdependence was observed among grain, straw, biological yields and the harvest index with RWC (r = 0.89–0.96) and quality parameters, viz, OC, CF and PC (r ≥ 0.95; 0.91; 0.85). These quality parameters were also positively correlated (r ≥ 0.97) among themselves and with RWC. In contrast, there was strong negative correlation among grain, straw biological yields and HI with WP (r = −0.69; −0.79; −0.76; −0.58), OP (r = −0.72; −0.70; −0.71; −0.69) and EA (r = −0.63; −0.68; −0.66; −0.57) (Table 6).

Table 6. Correlation matrix between mustard grain (GY), straw (SY), biological (BY) yields and harvest index (HI), as well as plant–water relations. RWC, relative water content; WP, water potential; OP, osmotic potential; TP, turgor potential. Quality parameters are oil content (OC), crude fiber (CF), protein content (PC) and erucic acid content (EC).

		* GY	* SY	* BY	* HI	* RWC	* WP	* OP	* TP	* OC	* PC	* CF	* EA
GY	Pearson Corr.	1	0.96	0.98	0.97	0.95	−0.69	−0.72	−0.15	0.96	0.81	0.77	−0.63
GY	*p*-value	–	2.08×10^{-7}	2.04×10^{-9}	5.47×10^{-8}	2.04×10^{-6}	0.012	0.007	0.620	2.76×10^{-7}	0.001	0.002	0.025
SY	Pearson Corr.	0.96	1	0.99	0.89	0.96	−0.79	−0.70	0.005	0.95	0.83	0.80	−0.68
SY	*p*-value	2.08E-07	–	1.16×10^{-11}	7.73×10^{-5}	4.91×10^{-7}	0.002	0.010	0.98	1.96×10^{-6}	7.95×10^{-4}	0.001	0.014
BY	Pearson Corr.	0.98	0.99	1	0.93	0.96	−0.76	−0.71	−0.056	0.96	0.83	0.80	−0.66
BY	*p*-value	2.04×10^{-9}	1.16×10^{-11}	–	9.27×10^{-6}	3.52×10^{-7}	0.003	0.008	0.860	4.26×10^{-7}	7.89×10^{-4}	0.001	0.017
HI	Pearson Corr.	0.97	0.89	0.93	1	0.89	−0.58	−0.69	−0.27	0.92	0.74	0.68	−0.57
HI	*p*-value	5.47×10^{-8}	7.73×10^{-5}	9.27×10^{-6}	–	7.57×10^{-5}	0.045	0.011	0.39	1.44×10^{-5}	0.005	0.013	0.049
RWC	Pearson Corr.	0.95	0.96	0.96	0.89	1	−0.74	−0.68	−0.02	0.97	0.91	0.85	−0.76
RWC	*p*-value	2.04×10^{-6}	4.91×10^{-7}	3.52×10^{-7}	7.57×10^{-5}	–	0.005	0.014	0.93	3.00×10^{-8}	3.38×10^{-5}	3.45×10^{-4}	0.003
WP	Pearson Corr.	−0.69	−0.79	−0.76	−0.58	−0.74	1	0.77	−0.18	−0.68	−0.60	−0.62	0.68
WP	*p*-value	0.012	0.002	0.003	0.045	0.005	–	0.003	0.571	0.013	0.037	0.029	0.014
OP	Pearson Corr.	−0.72	−0.70	−0.71	−0.69	−0.68	0.77	1	0.47	−0.71	−0.66	−0.70	0.74
OP	*p*-value	0.007	0.010	0.008	0.011	0.014	0.003	–	0.114	0.008	0.018	0.009	0.005
TP	Pearson Corr.	−0.159	0.005	−0.056	−0.271	−0.027	−0.182	0.479	1	−0.162	−0.197	−0.237	0.209
TP	*p*-value	0.620	0.987	0.860	0.392	0.932	0.571	0.114	–	0.614	0.538	0.457	0.512
OC	Pearson Corr.	0.967	0.951	0.964	0.927	0.979	−0.685	−0.715	−0.162	1	0.920	0.881	−0.705
OC	*p*-value	2.76×10^{-7}	1.96×10^{-6}	4.26×10^{-7}	1.44×10^{-5}	3.00×10^{-8}	0.013	0.008	0.614	–	2.19×10^{-5}	1.53×10^{-4}	0.010
PC	Pearson Corr.	0.816	0.831	0.832	0.746	0.913	−0.603	−0.665	−0.197	0.920	1	0.976	−0.829
PC	*p*-value	0.0012	7.95×10^{-4}	7.89×10^{-4}	0.0052	3.38×10^{-5}	0.0376	0.0181	0.538	2.19×10^{-5}	–	5.23×10^{-8}	8.54×10^{-4}
CF	Pearson Corr.	0.77	0.80	0.80	0.68	0.85	−0.62	−0.70	−0.23	0.88	0.97	1	−0.82
CF	*p*-value	0.002	0.001	0.001	0.013	3.45×10^{-4}	0.029	0.009	0.457	1.53×10^{-4}	5.23×10^{-8}	–	8.64×10^{-4}
EA	Pearson Corr.	−0.63	−0.68	−0.66	−0.57	−0.76	0.68	0.74	0.20	−0.70	−0.82	−0.82	1
EA	*p*-value	0.025	0.014	0.017	0.049	0.0038	0.014	0.005	0.512	0.010	8.54×10^{-4}	8.64×10^{-4}	–

* Grain (GY), straw (SY), biological (BY) yields and harvest index (HI), as well as plant–water relations. RWC, relative water content; WP, water potential; OP, osmotic potential; TP, turgor potential. Quality parameters are oil content (OC), crude fiber (CF), protein content (PC) and erucic acid content (EC).

4. Discussion

The cut-soiler-simulated PSSD was manually constructed in July 2018. The two types of soils had differential soil salinities at the beginning of experiment: the sandy loam saline soil had a higher salinity (~6 dS m^{-1}) and the heavy-texture soil had a lower salinity (3.02 dS m^{-1}) (Table 1). The salinity of both soil types declined continuously from its initial value and lower values were recorded in 2019–2020, which further decreased in 2020–2021 (Figure 3). The temporal decrease in soil salinity across both soil types and the application of saline irrigation water was due to the continuous removal of salts by cut-soiler PSSD. The higher rainfall in 2020–2021 (Figure 2) compared to the previous cropping season was another reason for the higher decline in soil salinity in the year 2020–2021. The soil salinity was the lowest in the upper surface layer (0–15 cm) and increased with the depth at the sowing of mustard, and the opposite trend was observed after mustard harvest (Figure 3). During the monsoon (rainy) season, soluble salts tended to leach down to lower soil layers; therefore, higher salinity values were observed in deeper layers at the time of sowing of mustard crop. On the other hand, during the ensuing post-rainy season (winter season), the use of saline water for irrigation and upward flux of soil salinity in the later growing period of mustard caused a higher accumulation of salts in surface soil layers. Such upward salt movement along with soil moisture takes place through capillary rise and the evaporation of water from the soil surface, as well as the transpiration by crop plants in due course.

Under the cut-soiler treatment, the lower salinity at all sampling stages and the lower buildup of salinity, especially in the upper soil layers, in the post-rainy season (after harvest) illustrated the effectiveness of cut-soiler drainage in salt removal (Figure 3b). Earlier preferential shallow subsurface drainage by cut-drains was found to be effective in reducing soil salinity by up to 44% near to cut-drains in comparison to control after one year of leaching salts in salt-affected regions of Uzbekistan [27], and the reduction in soil salinity was more prominent in the upper soil profile [20]. The sandy loam saline soil had a higher salinity than heavy-textured soil at all sampling stages. This was due to the initial salinity difference in these soils (Figure 3c). The net decrease in soil salinity was higher in 4 dS m^{-1} salinity water irrigation, followed by 8 dS m^{-1} and 12 dS m^{-1}. The lowest decline in soil salinity in 12 dS m^{-1} salinity water irrigation was due to the addition of more salts through irrigation water compared to lower-salinity water (Figure 3d). The increase in soil salinity due to the application of saline irrigation water has been previously reported [28]. This study recorded that the soluble and exchangeable salt concentration in soil solution also increased as the salinity of applied water increased. Gandahi et al. [29] have further added that EC, soluble cations and anions in saline irrigation water had the highest effect on soil EC. In our study, there was also an increase in soil salinity due to a cumulative buildup of salt with a higher Na^{+} concentration in applied saline water. Therefore, applying a higher volume of salty water resulted in a higher soil salinity in this study. However, Sharma and Tyagi [30] found that total salt removal depends on the leaching and drainage function of the soil type, which further depends upon the availability of good-quality irrigation water or rainfall for crop production in salty areas. Yadav et al. [31] advocated for an inexpensive degradable organic subsurface drainage material to satisfy the needs of initial drainage, low investment and a healthy soil environment.

Under the cut-soiler treatment, the moisture contents before sowing and after harvest of mustard crop were lower than the treatments without a cut-soiler (Figure 4). As far as the effect of soil type is concerned, the soil moisture content was significantly higher in heavy-texture soil than saline soil before sowing and after harvest. Before sowing and after the harvest of mustard crop, the application of the 4 dS m^{-1} irrigation water treatment led to relatively higher soil moisture contents of over 8 and 12 dS m^{-1}. Cut-soiler PSSD can help discharge excess water from a field to the open drainage area network even during a period with a high drainage water level. The higher extent of change in soil salinity and lower extent of change in in soil moisture in light-texture sandy loam saline soils was mainly due to its higher hydraulic conductivity and narrower range of moisture retention/release characteristics than the silty clay loam heavy-textured soil. The lower soil moisture content after the harvest of each successive crop may be due to a higher evapotranspiration caused by better crop growth and metabolic activities with the advancement of the crop season. Consequently, the crop water use consistently increased with the advancement in crop age, leading to a decline in soil moisture content in the soil profile [32].

The average mass balance of drained water (Table 2) indicated that the total volume of drained water and thus the amount of salt removal was directly related to the total water input available for leaching, mainly through rainfall as the same amount of irrigation water was applied in all studied durations. The amount of salt removal was also related to the salinity of drained water along with the water input. The drainage of water and salt was consistently higher during the rainy seasons. The maximum amounts of water (188.4 mm) and salt (1.7 kg) were drained out from 18 June to 18 October, followed by 20 May to 20 October (137.5 mm; 0.77 kg), when the maximum rainfall was received. The low drainage of water and salt from 19 May to 19 October was mainly due to the lesser rainfall in that year. There was very low (19 November to 20 April) or no drainage in the winter season. Lu et al. [33] reported the dependency of the drainage volume on the amount of input water for leaching, which influences the amount of salt removal and is also related to the soil salinity and thus the salinity (EC) of drained water.

More rainfall along with more hours of sunshine and relative humidity created relatively favorable conditions for crop growth in the year 2020. All these factors are conducive to production and have enhanced the seed and biomass yields of the crops. A better performance of different crops has been also been previously reported under congenial prevailing climatic conditions [34–37]. The cut-soiler drains have also facilitated the outward movement of salt along drainage water, leading to the lowering of soil salinity, especially in the succeeding crops. Mathew et al. [38] concluded that soil chemical properties tend to stabilize uniformly within two years of drainage provision and inevitably increase the crop growth and yield. Similarly, Feng et al. [39] assessed the sustainability of the effects of saline water irrigation under subsurface drainage conditions and found a lesser reduction in the yield of summer maize under subsurface drainage conditions in a two-year-long experiment. They further concluded that subsurface drainage measures provide important support for the sustainable utilization of saline water in irrigation.

Cut-soiler operation has been found to improve drainage conditions, leading to a lower buildup of soil salinity, which also contributes towards increased crop yields. Okuda et al. [27] reported a 20% increase in cotton yield after one year of preferential drainage by cut-drains in salt-affected fields in Uzbekistan. Accordingly, they concluded that shallow subsurface drainage was effective in reducing soil salinity and improving crop yields. Moreover, in our present study, improved drainage conditions in cut-soiler-operated plots further led to a lower soil salinity and, as a result, also contributed towards increased crop yields. The role of cut-soilers in discharging saline water and the management of salt-affected soils for optimum crop production has also been previously reported [40,41]. Thus, the reports of previous studies and our observations reveal that the saline drainage water of varying salinity levels can be productively utilized for the irrigation of winter crops, either directly or in combination with canal water. Nevertheless, the extent of salt leaching and crop establishment will depend on the total amount of monsoon rains received and the adequacy of subsurface drainage [30]. Salt stress caused inhibitory effects on yield attributes and yields at higher irrigation water salinity levels. The inhibitory effects of higher-irrigation water salinity level salt stress on yield attributes and yields were mainly caused as a result of osmotic shock, ion toxicity and nutritional imbalance, which caused a reduction in photosynthetic activity and other physiological abnormalities [42]. Similar findings of reductions in crop yield with the application of higher-irrigation water salinity have been previously reported [10,43,44].

The cut-soiler treatment recorded higher oil content, protein content and crude fiber (Table 4), but lower erucic acid levels in mustard seed. Singh et al. [45] also noticed that increasing salinity (water and soil) induced a decrease in mustard seed oil, protein and crude fiber contents but increased the erucic acid content as compared to the non-saline control. The reduction in seed oil content might be due to an increase in the osmotic pressure of the soil solution and imbalances in nutrients and essential elements [46] and the retarded development of seeds and plants in the early maturity stage in high salinity treatments [47].

The relative water content (RWC) was higher in the reproductive stage during 2020–2021. A higher water potential (WP) and osmotic potential were recorded (less negative values) at both stages in the year 2020–2021 (Table 5). The use of cut-soiler technology led to a significant improvement in plant–water relations under both sandy loam saline and heavy-texture soils. The work related to residue-filled cut-soiler PSSD is new until now, there were no reports available to support the results obtained. However, our observations clarified that improvements in soil physico-chemical properties through cut-soiler operation helps in enhancing the efficiency of water and nutrient use in mustard crop. The cut-soiler facilitated the draining out of excess water and dissolved salts from the crop rhizosphere that might have helped to improve the physiological efficiency of mustard.

Irrigation water salinity led to a rapid osmotic phase that hampered the growth of young leaves and a slower ionic phase that caused nutritional imbalance, leaf senescence and a reduction in the activities of enzymes involved in physiological mechanisms [48]. The relative water content (RWC), water potential (WP) and osmotic potential (OP) at vegetative and reproductive stages were significantly decreased at higher salinity levels, viz., 8 and 12 dS m^{-1} levels with respect to lower levels (Table 5). A high salt concentration in the root zone causes osmotic stress, which restricts the water absorption by the plants and causes cellular dehydration, and seems to be primarily responsible for decreases in WP, OP and RWC [49]. In addition, an increased salt load caused a reduction in root hydraulic conductivity, resulting in a decreased water flow from roots to shoot, and this decrease in water flow due to stress may cause a lowering of leaf water contents [50,51].

5. Conclusions

The cut-soiler PSSD effectively removed excess water and salts, especially during the rainy season, when the available water input for leaching is high. The drainage volumes were higher in the rainy season (April to October), i.e., 16.6, 7.76 and 12.0% during 2018, 2019 and 2020, with 1.7, 0.32 and 0.77 kg salt removal per lysimeter, but negligible in the post-rainy season. The amount of salt removal was also related to the salinity of drained water along with the water input. The reduction in soil salinity, with effective rainfall or irrigation events, was more in the upper surface layers and areas in close vicinity to the cut-soiler drain. Cut-soiler operation improved drainage conditions, leading to a reduction in soil salinity, and consequently increased mustard yield and quality. Additionally, the cut-soiler PSSD was found to efficiently manage the increases in salt load by applied irrigation water salinity up to 12.0 dS m^{-1}. Overall, the cut-soiler PSSD improved mustard seed yield by 31% and seed quality, in terms of higher oil, crude fiber and protein contents and a lower erucic acid content. Hence, the present study showed the potential of cut-soiler PSSD in the management of root zone salinity and crop residues for farmers of salt-affected areas.

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References

1. FAO. Food and Agriculture Organisation of the United Nations. Available online: https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf (accessed on 26 January 2022).
2. Hasanuzzaman, M.; Nahar, K.; Alam, M.; Bhowmik, P.C.; Hossain, M.; Rahman, M.M.; Fujita, M. Potential use of halophytes to remediate saline soils. *BioMed Res. Int.* **2014**, *14*, 589341. [CrossRef] [PubMed]
3. Mandal, S.; Raju, R.; Kumar, A.; Kumar, P.; Sharma, P.C. Current status of research, technology response and policy needs of salt-affected soils in India–a review. *J. Indian Soc. Coast. Agric. Res.* **2018**, *36*, 40–53.
4. CSSRI. *Vision 2050*; ICAR-Central Soil Salinity Research Institute: Karnal, India, 2015. Available online: https://cssri.res.in/download/vision_2050_cssri_karnal/?wpdmdl=3031 (accessed on 26 January 2022).
5. Thimmappa, K.; Singh, Y.; Raju, R.; Tripathi, R.S.; Kumar, S.; Sendhil, R.; Mitrannavar, D. Declining farm productivity and profitability due to soil degradation in North India. *J. Wheat Res.* **2015**, *7*, 45–51.
6. Mandal, A.K.; Sharman, R.C.; Singh, G.; Dagar, J.C. *Computerised Database on Salt-Affected Soils in India*; Technical Bulletin CSSRI, Karnal/2/2010; ICAR-Central Soil Salinity Research Institute: Karnal, India, 2010.
7. Sharma, D.K.; Thimmappa, K.; Chinchmalatpure, A.R.; Mandal, A.K.; Yadav, R.K.; Chaudhari, S.K.; Satyendra, K.; Sikka, A.K. *Assessment of Production and Monetary Losses from Salt-Affected Soils in India*; Technical Bulletin ICAR-CSSRI/Karnal/2015/05; ICAR-Central Soil Salinity Research Institute: Karnal, India, 2015; p. 99.
8. Sharma, D.K.; Singh, A. Salinity research in India-achievements, challenges and future prospects. *Water Energy Int.* **2015**, *58*, 35–45.
9. Lobell, D.B.; Burke, M.B.; Tebaldi, C.; Mastrandrea, M.D.; Falcon, W.P.; Naylor, R.L. Prioritizing climate change adaptation needs for food security in 2030. *Science* **2008**, *319*, 607–610. [CrossRef]
10. Yadav, T.; Kumar, A.; Yadav, R.K.; Yadav, G.; Kumar, R.; Kushwaha, M. Salicylic acid and thiourea mitigate the salinity and drought stress on physiological traits governing yield in pearl millet–wheat. *Saudi J. Biol. Sci.* **2020**, *27*, 2010–2017. [CrossRef]
11. Ritzema, H.P.; Satyanarayana, T.V.; Raman, S.; Boonstra, J. Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. *Agric. Water Manag.* **2008**, *95*, 179–189. [CrossRef]
12. Jalota, S.K.; Arora, V.K. Model-based assessment of water balance components under different cropping systems in north-west India. *Agric. Water Manag.* **2002**, *57*, 75–87. [CrossRef]
13. Boumans, J.H.; Van Hoorn, J.W.; Kruseman, G.P.; Tanwar, B.S. Water table control, reuse and disposal of drainage water in Haryana. *Agric. Water Manag.* **1988**, *14*, 537–545. [CrossRef]
14. Singh, A. On Farm Irrigation Water Management in Raya through Simulation Modeling under Saline Groundwater Conditions. Ph.D. Thesis, CCS Haryana Agricultural University, Hisar, India, 1999.
15. Singh, G.; Bundela, D.S.; Sethi, M.; Lal, K.; Kamra, S.K. Remote Sensing and Geographic Information System for Appraisal of Salt-Affected Soils in India. *J. Environ. Qual.* **2010**, *39*, 5–15. [CrossRef]
16. Minhas, P.S.; Gupta, R.K. *Quality of Irrigation Water: Assessment and Management*; Indian Council of Agricultural Research: New Delhi, India, 1992.
17. Maas, E.V.; Grattan, S.R. Crop yields as affected by salinity. *Agric. Drain.* **1999**, *38*, 55–108.
18. Singh, J.; Sharma, P.C. Comparative effects of soil and water salinity on oil quality parameters of *Brassica juncea*. *J. Oilseed Brassica* **2016**, *7*, 29–37.
19. Usda, N.R.C.S. *The Plants Database*; National Plant Data Center: Baton Rouge, LA, USA, 2013.
20. Okuda, Y.; Goto, K.; Kitagawa, I. A Trial of Desalinization by Using a Mole-Drain in the Republic of Uzbekistan. In *Development of Subsurface Drainage and Water-Saving Irrigation Technology for Mitigation of Soil Salinization in Uzbekistan*; Japan International Research Center for Agricultural Sciences (JIRCAS): Tshukuba, Japan, 2020; p. 65.
21. Neha; Yadav, G.; Yadav, R.K.; Kumar, A.; Rai, A.K.; Sehwag, M.; Onishi, J.; Omori, K.; Sharma, P.C. Desalinization effect of simulated Cut-soiler based residue filled preferential shallow sub surface drainage improves physiology and yield of rain-fed pearl millet in saline semiarid regions. *Land Degrad. Dev.* **2022**. [CrossRef]

22. Narjary, B.; Kumar, S.; Kamra, S.K.; Bundela, D.S.; Sharma, D.K. Impact of rainfall variability on groundwater resources and opportunities of artificial recharge structure to reduce its exploitation in fresh groundwater zones of Haryana. *Curr. Sci.* **2014**, *107*, 1305–1312.
23. Gabriel, J.L.; Almendros, P.; Hontoria, C.; Quemada, M. The role of cover crops in irrigated systems: Soil salinity and salt leaching. *Agric. Ecosyst. Environ.* **2012**, *158*, 200–207. [CrossRef]
24. Richards, L.A. *Diagnosis and Improvement of Saline and Alkali Soils*; USDA Agriculture Handbook; U.S. Government Printing Office: Washington, DC, USA, 1954; Volume 60, p. 160.
25. Weatherley, P. Studies in the water relations of the cotton plant: I. The field measurement of water deficits in leaves. *New Phytol.* **1950**, *49*, 81–97. [CrossRef]
26. Statistical Analysis System. *User's Guide: Statistics, Version 8.2*; SAS Institute: Cary, NC, USA, 2001.
27. Okuda, Y.; Onishi, J.; Shirokova, Y.I.; Kitagawa, I.; Kitamura, Y.; Fujimaki, H. Salt removal technology by shallow subsurface drainage in combination with a cut-drain. *J. Arid. Land Stud.* **2018**, *28*, 127–130.
28. Meena, M.D.; Joshi, P.K.; Narjary, B.; Sheoran, P.; Jat, H.S.; Chinchmalatpure, A.R.; Sharma, D.K. Effects of municipal solid waste compost, rice-straw compost and mineral fertilizers on biological and chemical properties of a saline soil and yields in a mustard–pearl millet cropping system. *Soil Res.* **2016**, *54*, 958–969. [CrossRef]
29. Gandahi, A.W.; Gandahi, R.; Sarki, M.S.; Buriro, M. Effect of saline groundwater on growth, fodder yield and ion content of various maize (*Zea mays* L.) cultivars. *Sci. Int.* **2015**, *27*, 3305–3309.
30. Sharma, D.P.; Tyagi, N.K. On-farm management of saline drainage water in arid and semi-arid regions. *Irrig. Drain.* **2004**, *53*, 87–103. [CrossRef]
31. Yadav, R.K.; Datta, A.; Dagar, J.C. Future Research Needs: Way Forward for Combating Salinity in Climate Change Scenario. In *Research Developments in Saline Agriculture*; Springer: Singapore, 2019; pp. 883–899.
32. Arvind, K.Y. Agro Physiological Traits for Drought Tolerance in Pearl Millet (*Pennisetum glaucum* L.). Ph.D. Thesis, Chaudhary Charan Singh Haryana Agricultural University, Hisar, India, 2013.
33. Lu, P.; Zhang, Z.; Sheng, Z.; Huang, M.; Zhang, Z. Assess effectiveness of salt removal by a subsurface drainage with bundled crop straws in coastal saline soil using HYDRUS-3D. *Water* **2019**, *11*, 943. [CrossRef]
34. Bandyopadhyay, K.K.; Pradhan, S.; Sahoo, R.N.; Singh, R.; Gupta, V.K.; Joshi, D.K.; Sutradhar, A.K. Characterization of water stress and prediction of yield of wheat using spectral indices under varied water and nitrogen management practices. *Agric. Water Manag.* **2014**, *146*, 115–123. [CrossRef]
35. Prasad, P.V.; Boote, K.J.; Allen, L.H., Jr. Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agric. For. Meteorol.* **2006**, *139*, 237–251. [CrossRef]
36. Meena, H.N.; Bhalodia, P.K.; Jat, R.S.; Vekaria, L.C. Prospects of using saline water for irrigation in groundnut (*Arachis hypogaea*)-pearl millet (*Pennisetum glaucum*) cropping system in saline black soils of Saurashtra. *Indian J. Agron.* **2012**, *57*, 122–126.
37. Wakchaure, G.C.; Minhas, P.S.; Ratnakumar, P.; Choudhary, R.L. Effect of plant bioregulators on growth, yield and water production functions of sorghum [*Sorghum bicolor* (L.) Moench]. *Agric. Water Manag.* **2016**, *177*, 138–145. [CrossRef]
38. Mathew, E.K.; Panda, R.K.; Nair, M. Influence of subsurface drainage on crop production and soil quality in a low-lying acid sulphate soil. *Agric. Water Manag.* **2001**, *47*, 191–209. [CrossRef]
39. Feng, G.; Zhang, Z.; Zhang, Z. Evaluating the sustainable use of saline water irrigation on soil water-salt content and grain yield under subsurface drainage condition. *Sustainability* **2019**, *11*, 6431. [CrossRef]
40. Chiba, K.; Kato, T.; Togashi, C.; Kanmuri, H. Effectiveness of desalinization by infiltration of water and desalinization of tsunami-hit farmlands in Miyagi Prefecture. *Water Land Environ. Eng.* **2012**, *80*, 3–6. (In Japanese)
41. Kaneko, T.; Murakawa, M.; Kozai, N.; Mitsugi, K. Desalting technique for illuviated salts soil at paddy field by using under-drainage. *J. Jpn. Soc. Irrig. Drain. Reclam. Eng. Jpn.* **2002**, *70*, 611–614.
42. Makarana, G.; Yadav, R.K.; Kumar, R.; Soni, P.G.; Yadav, T.; Yadav, M.R.; Meena, V.K. Fodder yield and quality of pearl millet (*Pennisetum glaucum* L.) Genotypes as influenced by salinity of irrigation water in north western India. *Indian J. Anim. Nutr.* **2017**, *34*, 56–63. [CrossRef]
43. Nadaf, S.K.; Al-Hinai, S.A.; Al-Farsi, S.M.; Al-Lawati, A.H.; Al-Bakri, A.N.; Ahmed, M.; Hussain, N. Differential Response of Salt Tolerant Pearl Millet Genotypes to Irrigation Water Salinity. In *The Monograph on Management of Salt-Affected Soils and Water for Sustainable Agriculture*; Mushtaque, A., Al-Rawahi, S.A., Hussain, N., Eds.; Sultan Qaboos University: Muscat, Oman, 2010; pp. 47–60.
44. Singh, J.; Sharma, P.C.; Sharma, S.K.; Rai, M. Assessing the effect of salinity on the oil quality parameters of Indian mustard (*Brassica juncea* L. Czern&Coss) using Fourier Transform Near-Infrared Reflectance (FT-NIR) spectroscopy. *Grasas Y Aceites* **2014**, *65*, e009.
45. Toorchi, M.; Naderi, R.; Kanbar, A.; Shakiba, M.R. Response of spring canola cultivars to sodium chloride stress. *Ann. Biol. Res.* **2012**, *2*, 312–322.
46. Cucci, G.; Rotunno, T.; De Caro, A.; Lacolla, G.; Di Caterina, R.; Tarantino, E. Effects of saline and sodic stress on yield and fatty acid profile in sunflower seeds. *Ital. J. Agron.* **2007**, *2*, 13–22. [CrossRef]
47. Kumar, A.; Mann, A.; Kumar, A.; Kumar, N.; Meena, B.L. Physiological response of diverse halophytes to high salinity through ionic accumulation and ROS scavenging. *Int. J. Phytoremediat.* **2021**. [CrossRef]

48. Greenway, H.; Munns, R. Mechanisms of salt tolerance in nonhalophytes. *Annu. Rev. Plant Physiol.* **1980**, *31*, 149–190. [CrossRef]
49. Nandwal, A.S.; Kukreja, S.; Kumar, N.; Sharma, P.K.; Jain, M.; Mann, A.; Singh, S. Plant water status, ethylene evolution, N2-fixing efficiency, antioxidant activity and lipid peroxidation in Cicer arietinum L. nodules as affected by short-term salinization and desalinization. *J. Plant Physiol.* **2007**, *164*, 1161–1169. [CrossRef]
50. Neto, M.T.C.; Reinhardt, D.H.; Ledo, C.A.d.S. Determination of water potential on mango trees by pressure chamber. *Acta Hort.* **2004**, *645*, 425–427. [CrossRef]
51. Pooja, D.; Nandwal, A.S.; Chand, M.; Singh, K.; Mishra, A.K.; Kumar, A.; Kumari, A.; Rani, B. Varietal variation in physiological and biochemical attributes of sugarcane varieties under different soil moisture regimes. *Indian J. Exp. Biol.* **2019**, *57*, 721–732.