sustainability

MDPI

Article

Quantitative Dissection of Salt Tolerance for Sustainable Wheat Production in Sodic Agro-Ecosystems through Farmers' Participatory Approach: An Indian Experience

Parvender Sheoran [1,*], Arvind Kumar [1], Raman Sharma [1], Kailash Prajapat [1], Ashwani Kumar [1], Arijit Barman [1], R. Raju [1], Satyendra Kumar [1], Yousuf Jaffer Dar [1], Ranjay K. Singh [1], Satish Kumar Sanwal [1], Rajender Kumar Yadav [1], Ved Prakash Chahal [2] and Parbodh Chander Sharma [1]

[1] ICAR—Central Soil Salinity Research Institute, Karnal 132001, India; Arvind.Kumar@icar.gov.in (Arvind Kumar); ramansharmakaushik@gmail.com (R.S.); Kailash.Prajapat@icar.gov.in (K.P.); Ashwani.Kumar1@icar.gov.in (Ashwani Kumar); Arijit.Barman@icar.gov.in (A.B.); R.Raju@icar.gov.in (R.R.); S.Kumar2@icar.gov.in (S.K.); Dar.Yousuf@icar.gov.in (Y.J.D.); RK.Singh2@icar.gov.in (R.K.S.); Satish.Sanwal@icar.gov.in (S.K.S.); RK.Yadav@icar.gov.in (R.K.Y.); parbodh.chander@icar.gov.in (P.C.S.)

[2] Indian Council of Agricultural Research, New Delhi 110001, India; vpchahal.icar@nic.in

* Correspondence: Parvender.Sheoran@icar.gov.in

Abstract: To explore the comparative effects of field sodicity (soil pH) and irrigation water residual alkalinity (RSC_{iw}) on physiological and biochemical attributes of salt tolerance, and crop performance of two wheat varieties (KRL 210, HD 2967), a total of 308 on-farm trials were carried out in sodicity affected Ghaghar Basin of Haryana, India. Salt tolerant variety KRL 210 maintained relatively higher leaf relative water content (RWC; 1.9%), photosynthetic rate (Pn; 5.1%), stomatal conductance (gS; 6.6%), and transpiration (E; 4.1%) with lower membrane injury (MII; −8.5%), and better control on accumulation of free proline (P; −18.4%), Na^+/K^+ in shoot (NaK_S; −23.1%) and root (NaK_R; −18.7%) portion compared to traditional HD 2967. Altered physiological response suppressed important yield-related traits revealing repressive effects of sodicity stress on wheat yields; albeit to a lesser extent in KRL 210 with each gradual increase in soil pH (0.77–1.10 t ha^{-1}) and RSC_{iw} (0.29–0.33 t ha^{-1}). HD 2967 significantly outyielded KRL 210 only at soil pH $\leq$ 8.2 and $RSC_{iw} \leq 2.5$ me L^{-1}. By comparisons, substantial improvements in salt tolerance potential of KRL 210 with increasing sodicity stress compensated in attaining significantly higher yields as and when soil pH becomes >8.7 and $RSC_{iw} > 4$ me L^{-1}. Designing such variety-oriented threshold limits of sodicity tolerance in wheat will help address the challenge to enhance crop resilience, closing the yield gaps and improve rural livelihood under the existing or predicted levels of salt stress.

Keywords: physiological adaptation; RSC water; salt tolerance mechanisms; sodic soils; wheat yield

check for updates

Citation: Sheoran, P.; Kumar, A.; Sharma, R.; Prajapat, K.; Kumar, A.; Barman, A.; Raju, R.; Kumar, S.; Dar, Y.J.; Singh, R.K.; et al. Quantitative Dissection of Salt Tolerance for Sustainable Wheat Production in Sodic Agro-Ecosystems through Farmers' Participatory Approach: An Indian Experience. *Sustainability* **2021**, *13*, 3378. https://doi.org/10.3390/su13063378

Academic Editor: Domenico Ronga

Received: 19 February 2021
Accepted: 9 March 2021
Published: 18 March 2021

1. Introduction

The degradation of natural resources and loss of socio-ecological resilience has increased the agricultural challenges and vulnerabilities manifold. Worldwide, a major obstacle confronting irrigated agriculture, especially in drought-prone arid and semiarid regions, is the anticipated shortage of freshwater supplies and competition from other water-use sectors; prompting farmers to explore the non-conventional water resources (saline or sodic) to complement the irrigation water demand [1–4]. The tendency to increase the irrigation water use efficiency and inappropriately managed poor quality water for irrigation over a period of time has witnessed widespread increase in land and environmental degradation and associated salt accumulation [5,6]. If current trends continue unabated, the conservative estimate suggests that, by 2050, approximately 50% of the world agriculture will be affected by salinity and sodicity related problem and associated hazards [7]. In India, nearly 6.74 million hectares (m ha) of agricultural landscape is salt affected; realizing an anticipated production and monetary loss of US $3.5 billion annually [8]. This problem would be more critical in agriculturally important Indo-Gangetic region where almost 2.7 m ha of salt affected lands have underlying aquifers of poor quality water [9].

Irrigation-induced sodicity in soils is a major environmental constraint adversely affecting agricultural sustainability in water guzzling rice–wheat system [10,11]. Indiscriminate use of sodic water containing high proportions of sodium (Na^+) and a predominance of carbonates ($CO_3{}^{2-}$) and bicarbonates ($HCO_3{}^-$) results in dispersion of clay particles [12,13]. Sodicity induced disruptions of soil structure (reduced infiltration, hydraulic conductivity, and surface crusting) makes it difficult for plants to get established and obtain adequate water and nutrients [14], hampers the root penetration [15], and restricts the metabolic and enzymatic activities [16]. These physical and nutritional constraints to growing plants negatively affect the crop productivity [6,17].

Regaining the agricultural potential of degraded sodic lands is important to sustain food and livelihood security and associated economic development in the affected regions. Experimental evidences suggests the importance of synergizing adaptive and mitigation strategies to minimize the adverse effects of irrigation water induced soil sodification through improved water management systems, desirable soil structure and its stability, and appropriate crop planning [13,18,19]. Use of chemical (mineral gypsum) and organic (pressmud, farm yard manure, etc.) amendments helps in alleviating the adverse effects of sodic soils on crop growth and productivity [10,12,20]; however, the required quantity of material invariably involves higher production and application costs, which are generally beyond the economic reach of resource poor small landholders inhabiting such areas. Another strategy could be appropriate selection of crops, cropping pattern and varieties having better tolerance to the ambient or predicted level of soil sodicity [9,21]. Genetic variability for salt tolerance within a crop and/or plant species offers an opportunity to improve morpho-physiological adaptation and harvest reasonable yields under stress conditions [11,22]. This plant-assisted reclamation approach is perceived to be more realistic and economically sustainable; further reducing dependence on costlier ameliorants, and associated drainage problems and environmental footprints [23].

Systematic research on wheat improvement for salt tolerance in India was initiated in early 1970s at the Indian Council of Agricultural Research (ICAR)—Central Soil Salinity Research Institute (CSSRI), Karnal. Various approaches, including selection and gene introgression from landraces into adapted cultivars, were applied to improve the salt tolerance mechanisms (physiological adaptation and agronomic efficiency) in wheat. First successful deployment of salt tolerance with high yielding background using conventional approach was achieved in wheat through the release of salt tolerant KRL 1–4 in 1990. Thereafter, three salt tolerant wheat varieties; KRL 19 (2000), KRL 210 (2010), and KRL 213 (2010) have been released at the National level for salt affected regions of the country (www.cssri.res.in (accessed on 19 February 2021)). Despite their potential importance in stabilizing the farm production, the famers' technical know-how and field adaptability of tolerant varieties is quite low in wheat growing areas mostly at risk of salt induced land degradation. To improve their current understanding and sustain wheat production in sodic-water irrigated soils, ICAR led 'Farmer FIRST' Project (FFP) was implemented by CSSRI, Karnal in salt-affected Ghaghar Basin of Haryana, India. This program provides a strong farmer–scientist interface, linking formal and informal knowledge, technology assemblage, and conduct of participatory research to refine and develop demand-driven, location-specific technologies and strengthening rural livelihood. With this initiative, the present investigation was carried out in participatory mode with the objectives to: (i) quantify the adverse effects of soil sodicity and residual alkalinity in irrigation water on the performance of two wheat varieties [KRL 210 (salt tolerant variety released in 2010 for cultivation in saline and alkaline ecosystems; pedigree-PBW65/2*PASTOR. 2010), and HD 2967 (the most operable variety released in 2011 for cultivation in Northern Plain Zones; pedigree: ALD/COC//URES/HD2160M/HD2278)]; (ii) ascertain the extent of differences in morpho-physiological parameters of plant salt tolerance over a broad range of sodicity stress (soil and water); and (iii) defining the critical limits of sodicity tolerance for varietal selection and harness the yield gains under their local farm situations. We hypothesized that using tolerant varieties having better environmental adaptability and stable production under stress conditions will improve farmers livelihood in sodic soils irrigated with marginal (alkali) quality water.

2. Materials and Methods

2.1. The Study Locations

A total of five villages (Sampli Kheri, Kathwar, Mundri, Geong, and Bhaini Majra) typically representing salt affected Ghaghar basin (29.762°–29.838° N and 76.426°–76.518° E) were purposively selected under the Farmer FIRST project in Kaithal district of Haryana, India. About two-thirds of the Indian farmers belong to small landholder (size < 2 ha) [24]. As such, the cultivated area is dominated by rice–wheat monoculture, and crop production alone contributes ~64% of the total household income. Formal discussions with key informants revealed that continuous irrigation with poor quality water (RSC_{iw} > 2.5 me L^{-1}; permissible limit for safe use of sodic water in agricultural crops) for more than two decades and farmers' traditional practices (soil, crop, and water) for sodicity management concomitantly increased the extent and distribution of sodic soils (soil pH_2 > 8.5; 1:2 soil–water suspension; hereinafter designated as soil pH only and exchangeable sodium percentage, ESP > 15%) in the area; negatively impacting crop productivity.

The climate is subtropical semi-arid with dry summer and cool winters. On an average approximately 760 mm of rainfall is received annually between June and September months. Winter season remains mostly dry except for few cyclic rains in January–February due to western disturbances. Occasionally, prolonged water stagnation due to intense rainfall or an irrigation event in inherent sodic (dispersive) soils having poor infiltration further compounds the agricultural vulnerability. In addition, timely availability of good quality seeds, and farmers' knowledge regarding tolerant varieties for stress-prone areas contributes towards poor crop harvests.

2.2. Delineation of Soil Sodicity, Nutrient Status and Irrigation Water Quality

Grid (1 km × 1 km)-based soil and water sampling covering 3247 ha area across selected villages was done in May–June 2017 to delineate the extent and distribution of soil sodicity and irrigation water quality. Following this criterion, a total of 283 groundwater samples were collected from locally installed running tubewells. Irrigation water quality parameters viz., electrical conductivity (EC_{iw}), pH_{iw}, and cationic [(sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+})] and anionic [carbonate ($CO_3{}^{2-}$) and bicarbonate ($HCO_3{}^-$)] concentrations were determined following the standard analytical procedures as described by [25]. Following relationships were used to compute the sodium adsorption ratio (SAR) and residual alkalinity in irrigation water (RSC_{iw}) with concentration of all cations and anions expressed in me L^{-1} as:

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+}+Mg^{2+})}{2}}} \quad (1)$$

$$RSC_{iw} = (CO_3{}^{2-} + HCO_3{}^-) - (Ca^{2+} + Mg^{2+}) \quad (2)$$

Composite soil samples (0–15 cm depth) from 337 locations were drawn with soil auger by randomly selecting five places representative of the overall field. These samples were air dried, ground, and passed through 2-mm sieve to separate the impurities, and later stored in polybags. Laboratory analysis was done to estimate the soil pH and electrical conductivity (EC) potentiometrically using a digital meter (Eutech Model; pH 700 and CON 700, respectively) [26]. The collected soil samples were further processed to determine the soil available nitrogen ($KMnO_4$ mineralizable N, Kjeldahl digestion) [27], phosphorus (Olsen's P, 0.5 M $NaHCO_3$ extraction) [28], and potassium (NH_4OAc extractable K by emission spectrophotometry; 1 M neutral NH_4OAc-extractable K [29]. The concentration of DTPA extractable zinc (Zn) was estimated with atomic absorption spectrophotometer (Model: ZEEnit 700p, Analytika Jena, Germany).

Spatial variability, mapped through Ordinary Kriging Interpolation method, revealed that about 40% of the sampled area had sodicity (soil pH > 8.5) problem of varying degrees [30], while only 10% of the underground water was of good quality (RSC_{iw} < 2.5 me L^{-1}; EC_{iw} < 2 dS m^{-1}; SAR <10) [31] (Figure 1). Majority area had underground water with bicarbonate ($NaHCO_3^-$) rich residual alkalinity; alkali water (62.7%), marginally alkali (17.4%), and highly alkali (9.2%). Nearly 44% of total cultivated lands were characterized with RSC_{iw} of 4.5–5.5 me L^{-1}; maximum area in Bhaini Majra (84%), followed by Geong (66%), and Kathwar (45%) villages (Figure 1). The initial soil status revealed that the majority of the sodic soils in the study area had low N, medium to high P, high K, and low to medium Zn content in the topsoil; posing physical and nutritional constraints to growing plants (Supplementary Figure S1).

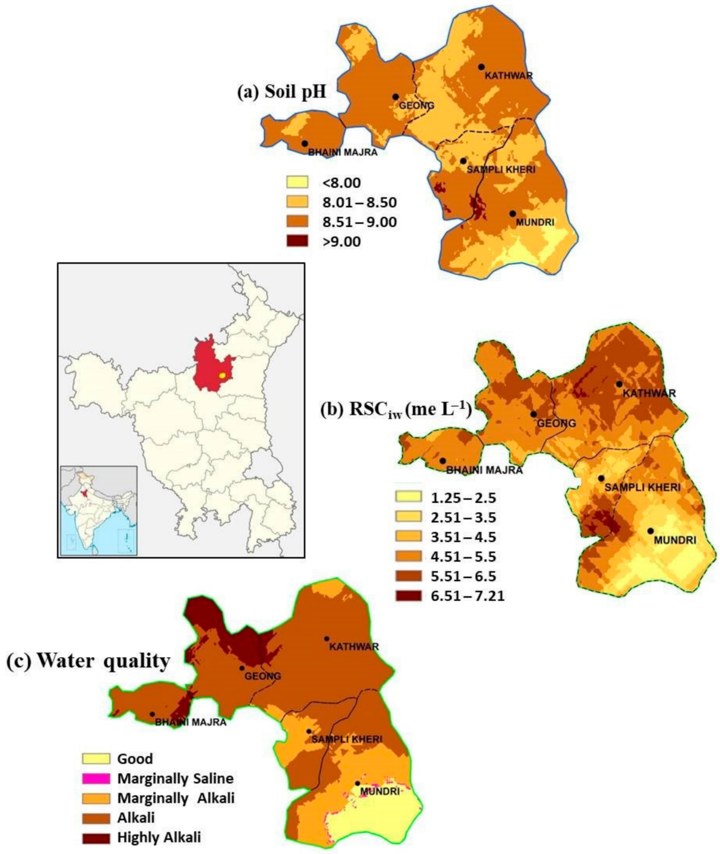

Figure 1. Maps showing the extent and distribution of (**a**) sodic soils, (**b**) residual alkalinity in irrigation water, and (**c**) water quality status in the study area.

2.3. Experimental Procedure and Treatment Details

To understand the mechanism of plants salt tolerance and changes in physiological and yield-related traits in response to variable sodicity stress (FPT–I), farmers' fields were grouped into 6 categories viz. (i) soil pH $\leq$ 8.25 and $RSC_{iw} \leq$ 2.5 me L^{-1} (SS1), (ii) soil pH 8.25–8.50 and RSC_{iw} 2.5–3.5 me L^{-1} (SS2), (iii) soil pH 8.50–8.75 and RSC_{iw} 3.5–4.5 me L^{-1} (SS3), (iv) soil pH 8.75–9.00 and RSC_{iw} 4.5–5.5 me L^{-1} (SS4), (v) soil pH 9.00–9.25 and RSC_{iw} 5.5–6.5 me L^{-1} (SS5), and (vi) soil pH $\geq$ 9.25 and $RSC_{iw} \geq$ 6.5 me L^{-1} (SS6). Based on their willingness to participate, three farmers (having sown CSR 30 Basmati in previous *kharif* season) in each category were selected to reduce the experimental error due to field heterogeneity and management practices. These on–farm trials were carried out for three years consecutively in a factorial-randomized block design with two replications at each site, keeping a plot size of 500–800 m^2. Field locations and initial soil and water quality status of selected sites are provided in Supplementary Table S1.

In addition, a total of 308 farmers' participatory trials (FPT) were also conducted over three years (2017–2018 to 2019–2020) in 'Farmer FIRST Adopted Villages' to evaluate the performance of two wheat varieties; KRL 210 (salt tolerant, dwarf statured, medium bold seeded variety) and HD 2967 (highly adapted variety in the area) in high RSC_{iw} irrigated sodic soils (FPT–II). Both the varieties were simultaneously grown in farmers' managed plots keeping two replications at each site. Depending on individual farmers' landholding, the study plots varied between 0.2 ha (small and marginal farmers) to 0.4 ha (medium and large farmers) in size. Each farmer was taken as a replicate and yield (4 pooled measurements; 2 observations per replications) was recorded at crop maturity. Details regarding farmers' managed crop production practices are provided in Supplementary Table S2. Linear regression model also indicated strong positive relationship (R^2 = 0.69) between estimated soil sodicity and underground water RSC in collected soil and water samples from selected sites (Figure 2).

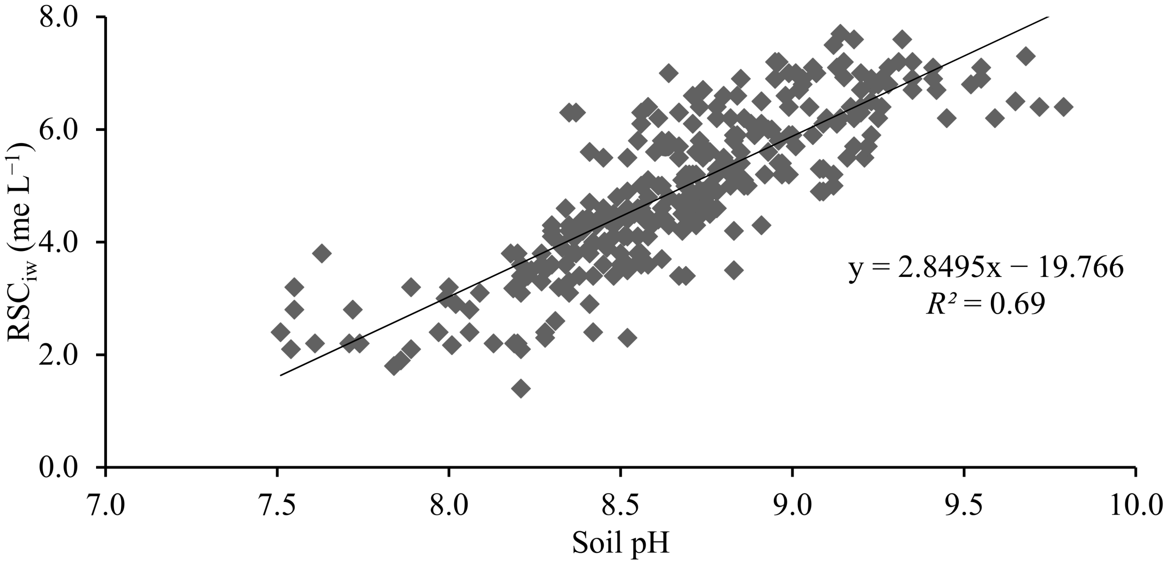

Figure 2. Relationship between irrigation water residual alkalinity and estimated soil sodicity across the sampled locations (n = 308).

Seeds of each variety (KRL 210 and HD 2967) were directly planted with 9-row (22.5 cm apart) zero till seed–cum–fertilizer drill during the first fortnight of November at the rate of 125 kg ha^{-1}. The crop was fertilized with 150 kg N (urea, 46%N), 26 kg P (di-ammonium phosphate, 18%N and 46% P_2O_5) and 50 kg K ha^{-1} (muriate of potash, 60% K_2O). Full P, K, and 1/3rd N (urea) was applied at the time of sowing while the remaining N was applied in 2 equal splits with first (25–35 days after sowing, DAS) and second (45–55 DAS) irrigation. Since there was no canal network, farmers' applied 2–3 irrigations with available RSC water depending on the crop water requirements and seasonal variations in precipitation received. Adequate measures to control weeds, insects, and diseases were taken to avoid yield losses.

2.4. Assessment of Physiological Parameters and Yield-Related Traits (FPT–I)

Physiological parameters of crop growth in response to sodicity stress viz., net photosynthesis (Pn), stomatal conductance (gS), and transpiration rate (E) were measured at flowering stage using a portable gas exchange system (LI–6400, LICOR Inc., Lincoln, NE, USA). Fully expanded leaves (3 readings in each plot) were placed within the sample chamber where gas exchange measurements were carried out under saturated light conditions (photosynthetically active radiations, PAR; 1000 µmol m^{-2}) maintaining 500 µmol s^{-s} air flow rate, 400 µmol mol^{-o} CO_2 concentrations, and 27 ± 0.8 °C leaf temperature. The same leaves were used for determining the leaf relative water content (RWC) [32], membrane injury index (MII) [33], and proline content (P) [34]. Shoot and root samples were washed with deionized water, oven dried at 70 °C for 48 h and then acid digested with HNO_3:$HClO_4$ in 3:1 ratio [35]. Digested samples were filtered, and concentrations of Na^+ and K^+ were determined using a flame photometer (Systronics Ltd., India).

Yield-related traits were recorded on 20 representative plants taken from the quadrants used to measure the grain yields in both varieties. A sub-sample of 1000-grains from each lot was randomly counted and weighed to record the 1000-grains weight. The yield data were recorded from two random places of 16 m^2 (4 m × 4 m quadrate) area in each plot when the plants were fully mature. These samples were sun dried, threshed manually, and weighed to measure the grain yield (t ha^{-1}) after adjusting it to 14% moisture content.

2.5. Farmers' Preference for Crop Variety Traits

The cultivated varieties were further evaluated by men and women farmers soliciting individual perception and extensive knowledge on specific plant and grain characteristics that can influence the adoption and rejection of a particular variety in an area. A scale of 1 to 5 was used to count the individualistic preference; 1 as least preferred, 5 as most preferred. The evaluation was conducted in two phases; first during the reproductive phase to get an idea of the desirable plant traits suiting the local farm situations, and second after crop harvest to estimate their yield potential and confirm the food-quality traits. Trait-wise preference score was computed accordingly by counting the difference between the total number of positive and negative votes divided by the total votes.

2.6. Statistical Analysis

The performance of crop varieties across six levels of sodicity stress was evaluated by performing 2–way analysis of variance (ANOVA) for all the physiological and yield-related traits (FPT–I) as $y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \epsilon_{ijk}$, where $i = 1 \ldots\ldots I$, $j = 1 \ldots\ldots J$, $k = 1 \ldots\ldots n_{ij}$; where α_i and βj parameters represent the main effects of soil sodicity and varieties, respectively, and ($\alpha\beta ij$) represents an interaction effect. The measured variables were subjected to Spahiro–Wilk test (W) test for their normality distribution [36]. The mean values following normal distribution were subjected to ANOVA using the statistical software SAS (v9.0, SAS Inc., Cary, NC, USA) in a factorial-randomized block design. A total of three years data were pooled to illustrate the treatments effects (varieties and sodicity stress) after testing the homogeneity of error variance by Bartlett's Chi Square test. Unless stated otherwise, differences between treatment means were compared using least significant difference (LSD) test at 5% level of significance.

For comparing the relative performance of two varieties (salt tolerant KRL 210 and locally adapted HD 2967) with increasing salt stress (FPT–II), the mean grain yields harvested over 308 locations were subjected to two tailed *t*-test (Pr > | t |). Changes in grain yield for each variety in response to variable soil pH and RSC_{iw} was also computed using regression coefficients at 95% confidence interval to enable selecting the better variety under the existing or predicted conditions of sodicity stress. Association between important physiological and agronomic traits with crop yield was established by the Pearson's correlation coefficient (*r*).

3. Results

3.1. Morpho-Physiological Adaptation to Sodicity Stress

3.1.1. Plant Water Relations and Membrane Stability

Traditionally cultivated wheat cultivar HD 2967 exhibited lower leaf relative water content (RWC) in comparison to salt tolerant KRL 210 at each level of sodicity stress (Table 1). The leaf RWC decreased from 81.3 to 71.4% in KRL 210 and 80.9 to 68.6% in HD 2967 with the increase in RSC_{iw} induced sodicity stress from SS1 (soil pH < 8.25 and RSC_{iw} < 2.5 me L^{-1}) to SS6 (soil pH > 9.25 and RSC_{iw} > 6.5 me L^{-1}). Across varieties, the magnitude of reduction in leaf RWC was 1.5% for SS2, 2.8% for SS3, 5.7% for SS4, 9.0% for SS5, and 11.7% for SS6 in KRL 210 compared to SS1 conditions. In contrast, the corresponding gradual reduction remained 1.2, 5.2, 8.0, 13.2, and 15.6%, respectively, in HD 2967. On an average, HD 2967 had 1.8% lower leaf RWC in comparison to KRL 210.

Table 1. Changes in physiological parameters of plant adaptation in two rice varieties (KRL 210 and HD 2967) in response to variable sodicity (soil and irrigation water) stress at farmers' fields (FPT–I, mean of 3 years).

Varieties	**Sodicity Stress ***						**Mean**	***p*-Value**
	SS1	**SS2**	**SS3**	**SS4**	**SS5**	**SS6**		
Relative water content (RWC, %)								
KRL 210	81.3	80.1	78.6	76.3	73.6	71.4	76.8 ^{A}	S: <0.0001
HD 2967	80.9	79.9	77.1	74.8	70.6	68.6	75.4 ^{B}	V: 0.0145
Mean	81.1 ^{A}	80.0 ^{A}	77.9 ^{B}	75.6 ^{B}	72.1 ^{D}	70.0 ^{E}		S × V: 0.0327
Membrane injury index (MII, %)								
KRL 210	28.1	28.4	28.8	29.4	31.9	34.1	30.1 ^{B}	S: <0.0001
HD 2967	29.5	29.6	30.1	32.7	36.9	38.3	32.9 ^{A}	V: <0.0001
Mean	28.8 ^{D}	29.0 ^{D}	29.5 ^{D}	31.1 ^{C}	34.4 ^{B}	36.2 ^{A}		S × V: 0.0003
Photosynthetic rate (Pn, µmol CO_2 m^{-2} s^{-1})								
KRL 210	18.1	17.9	17.3	16.2	15.7	13.7	16.5 ^{A}	S: <0.0001
HD 2967	18.6	18.4	17.1	15.6	13.8	12.1	15.7 ^{B}	V: 0.0009
Mean	18.4 ^{A}	18.2 ^{A}	17.2 ^{B}	15.9 ^{C}	14.8 ^{C}	12.9 ^{D}		S × V: 0.0001
Stomatal conductance (gS, mmol H_2O m^{-2} s^{-1})								
KRL 210	1.31	1.26	1.25	1.14	1.02	0.83	1.13 ^{A}	S: <0.0001
HD 2967	1.34	1.31	1.19	1.01	0.86	0.65	1.06 ^{B}	V: <0.0001
Mean	1.32 ^{A}	1.28 ^{A}	1.22 ^{B}	1.08 ^{C}	0.94 ^{D}	0.74 ^{E}		S × V: 0.0001
Transpiration rate (E, mmol H_2O m^{-2} s^{-1})								
KRL 210	2.62	2.58	2.42	2.23	2.02	1.82	2.28 ^{A}	S: <0.0001
HD 2967	2.66	2.61	2.37	2.11	1.80	1.61	2.19 ^{B}	V: 0.0008
Mean	2.64 ^{A}	2.59 ^{A}	2.40 ^{B}	2.17 ^{C}	1.91 ^{D}	1.72 ^{E}		S × V: 0.0054
Proline content (P, mg g^{-1})								
KRL 210	0.128	0.156	0.216	0.282	0.417	0.670	0.311 ^{B}	S: <0.0001
HD 2967	0.097	0.143	0.204	0.312	0.572	0.856	0.381 ^{A}	V: <0.0001
Mean	0.113 ^{F}	0.150 ^{E}	0.210 ^{D}	0.297 ^{C}	0.494 ^{B}	0.763 ^{A}		S × V: <0.0001
Shoot Na^+/K^+ ratio (NaK_S)								
KRL 210	0.147	0.158	0.172	0.194	0.216	0.269	0.193 ^{B}	S: <0.0001
HD 2967	0.176	0.189	0.206	0.247	0.309	0.378	0.251 ^{A}	V: <0.0001
Mean	0.161 ^{E}	0.173 ^{DE}	0.189 ^{D}	0.221	0.263 ^{B}	0.324 ^{A}		S × V: <0.0001
Root Na^+/K^+ ratio (NaK_R)								
KRL 210	0.306	0.341	0.373	0.431	0.502	0.589	0.425 ^{B}	S: <0.0001
HD 2967	0.359	0.402	0.446	0.527	0.632	0.766	0.523 ^{A}	V: <0.0001
Mean	0.332 ^{F}	0.371 ^{E}	0.410 ^{D}	0.479 ^{C}	0.567 ^{B}	0.677 ^{A}		S × V: <0.0001

* SS1: soil pH ≤ 8.25 and RSC_{iw} ≤ 2.5 me L^{-1}; SS2: soil pH 8.25–8.50 and RSC_{iw} 2.5–3.5 me L^{-1}; SS3: soil pH 8.50–8.75 and RSC_{iw} 3.5–4.5 me L^{-1}; SS4: soil pH 8.75–9.00 and RSC_{iw} 4.5–5.5 me L^{-1}; SS5: soil pH 9.00–9.25 and RSC_{iw} 5.5–6.5 me L^{-1}; SS6: soil pH ≥ 9.25 and RSC_{iw} ≥ 6.5 me L^{-1}. Data are mean value of 54 pooled measurements values with different superscript (A–F) letters across sodicity stress (within row) and varieties (within column) show the significant difference at p = 0.05 according to least significant difference test for separation of mean. data followed by different superscript letters across sodicity stress (within row) and varieties (within column) differ significantly ($p \leq 0.05$) using least significant difference test.

Continued irrigation with RSC water and the resultant salt stress caused injury to the leaf membranes; increasing the membrane injury index (MII) from 28.8 (SS1) to 36.2% (SS6) on mean basis (Table 1). Within varieties, the increase in MII was invariably lower in KRL 210 compared to HD 2967 with each gradual increase in sodicity stress. Overall, RSC_{iw} induced sodicity stress resulted in 9.3% higher MII in HD 2967 compared to its counterpart KRL 210.

3.1.2. Gas Exchange Parameters

Imposition of stress conditions suppressed Pn by 30%, gS by 44%, and E by 35% with increasing sodicity stress from SS1 to SS6 level (Table 1). On an average, salt tolerant KRL 210 exhibited 24% reduction for Pn, 37% for gS and 31% for E as against the higher extent of 35, 52, and 40%, respectively, in HD 2967. It is noteworthy that HD 2967 performed better in fields having soil pH < 8.5 and RSC_{iw} < 3.5 me L^{-1} (SS2), thereafter, KRL 210 acclaimed better plant acclimatization in respect of gas exchange (Pn, gS, and E) parameters. Each gradual increase in sodicity stress decreased Pn by 1, 3, 6, 8, and 9%; gS by 4, 1, 9, 11, and 19%, and E by 2, 6, 8, 9, and 10% in KRL 210, while the corresponding decline of 1, 7, 9, 12, and 13% in Pn; 2, 9, 14, 17, and 24% in gS, and 2, 9, 11, 12, and 13% in E was observed in case of HD 2967. Averaged across variable sodicity stress, KRL 210 attained 5.1% higher Pn, 6.6% higher gS, and 4.1% higher E compared to HD 2967.

3.1.3. Biochemical and Ionic Balances

Concomitant increase in accumulation of free proline (P), and Na^+/K^+ ratio in shoot (NaK_S) and root (NaK_R) portion was observed with increasing soil sodification; though the relative hike was more pronounced in locally adapted HD 2967 compared to salt tolerant KRL 210 (Table 1). Highest P (791 mg g^{-1}), NaK_S (0.324) and NaK_R (0.677) was recorded at SS6 level. The relative rate of increase remained 33, 40, 41, 66, and 60% in P; 8, 11, 15, 19, and 23% in NaK_S, and 9, 11, 17, 17, and 21% in NaK_R with each gradual increase in sodicity stress compared to preceding values.

Varietal differences were observed in the accumulation of free proline under different levels of sodicity stress; as evident by an abrupt increase of 8.8 times in HD 2967 at SS6 compared to SS1 as against the 5.2 times higher accumulation in KRL 210 under the similar situations (Table 1). With the increase in sodicity stress, substantial increase in sodium accumulation was noticed in tolerant KRL 210 also but to a lesser extent as compared to HD 2967. In HD 2967, Na^+/K^+ ratio increased from 0.18 to 0.38 in shoot and 0.37 to 0.77 in root portion attaining a 115 and 108% increase, respectively. While the tolerant KRL 210 resisted the change to a greater extent elucidating 83% increase in NaK_S and 86% increase in NaK_R at the same level of sodicity stress.

3.1.4. Morphometric Observations (FPT–I)

Collateral reductions in yield-related traits were noticed with each incremental sodicity stress, but the adverse effect was relatively lower in salt tolerant KRL 210 compared to traditionally cultivated HD 2967 (Table 2). The number of effective tillers (ET) decreased from 73 to 58 in KRL 210, and 72 to 55 in HD 2967; indicating reductions of more than 20 and 24%, respectively. Compared to SS1, marked reductions in spikelets $spike^{-1}$ (SS; 12 and 16%), grains $earhead^{-1}$ (GE; 21 and 30%) and 1000-grain weight (GW; 10 and 12%) were observed for both varieties at SS6. On an average, the salt tolerant KRL 210 had higher mean ET (3.9%), SS (1.6%), GE (4.8%), and GW (0.7%) in comparison to HD 2967. Across varieties, there were non-significant differences in yield attributes only up to SS2; thereafter mean reductions of 3.6, 6.2, 5.1, and 6.2% in ET; 6.1, 2.2, 5.5, 1.7% in SS; 5.8, 4.1, 9.8, 12.1% in GE, and 3.7, 1.9, 2.5, 4.6% in GW was noticed with each gradual increase in RSC_{iw} induced soil sodification over the preceding values for respective parameters (Table 2).

In FPT–I, sodicity stress induced by continuously irrigating with water having residual alkalinity of variable degrees negatively affected the crop production causing 4.7, 6.4, 6.9, 5.8, and 6.6% reduction in mean grain yield (average of two varieties) with each successive increase in sodicity stress compared to the preceding values (Table 3). The performance of salt tolerant KRL 210 was found relatively better than HD 2967 (except at SS1); albeit to a greater extent with increasing sodicity stress as evident by 1.1 (SS2) to 8.7% (SS5) yield superiority over the later.

Table 2. Effect of sodicity (soil and irrigation water) stress on yield-related traits and grain yield of two rice varieties (KRL 210 and HD 2967) at farmers' fields (FPT–I, mean of 3 years).

Varieties	Sodicity Stress *						Mean	*p*-Value
	SS1	SS2	SS3	SS4	SS5	SS6		
			Effective tillers (No. mrl^{-1})					
KRL 210	72.8	70.6	68.7	64.5	62.4	58.1	66.2 ^{A}	S: <0.0001
HD 2967	71.9	69.6	66.4	62.1	57.9	54.7	63.7 ^{B}	V: 0.0098
Mean	72.3 ^{A}	70.0 $^{A B}$	67.5 ^{B}	63.3 ^{C}	60.1 ^{C}	56.4 ^{D}		S × V: 0.8715
			Spikelets $spike^{-1}$					
KRL 210	19.4	19.5	18.9	18.4	17.5	17.1	18.5	S: <0.0001
HD 2967	19.8	20.1	18.4	17.9	16.8	16.6	18.3	V: 0.4517
Mean	19.6 ^{A}	19.8 ^{A}	18.6 ^{B}	18.2 $^{B C}$	17.2 $^{C D}$	16.9 ^{D}		S × V: 0.6612
			Grains $earhead^{-1}$					
KRL 210	65.1	64.8	62.5	59.8	53.8	47.4	58.9 ^{A}	S: <0.0001
HD 2967	63.8	63.6	58.4	56.2	50.7	44.6	56.2 ^{B}	V: 0.0061
Mean	64.5 ^{A}	64.2 ^{A}	60.5 ^{B}	58.0 ^{C}	52.3 ^{D}	46.0 ^{E}		S × V: 0.9188
			1000-grain weight (g)					
KRL 210	42.4	42.9	41.6	40.7	39.8	38.1	40.9	S: <0.0001
HD 2967	42.6	42.8	41.1	40.3	39.3	37.3	40.6	V: 0.0670
Mean	42.5 ^{A}	42.9 ^{A}	41.3 ^{B}	40.5 ^{C}	39.5 ^{D}	37.7 ^{E}		S × V: 0.6996
			Grain yield (t ha^{-1})					
KRL 210	4.61	4.44	4.22	3.98	3.78	3.53	4.09 ^{B}	S: <0.0001
HD 2967	4.66	4.29	4.05	3.72	3.48	3.25	3.91 ^{A}	V: <0.0001
Mean	4.63 ^{F}	4.37 ^{E}	4.14 ^{D}	3.85 ^{C}	3.63 ^{B}	3.39 ^{A}		S × V: <0.0001

mrl^{-1}: per meter row length; * SS1: soil pH ≤ 8.25 and RSC_{iw} ≤ 2.5 me L^{-1}; SS2: soil pH 8.25–8.50 and RSC_{iw} 2.5–3.5 me L^{-1}; SS3: soil pH 8.50–8.75 and RSC_{iw} 3.5–4.5 me L^{-1}; SS4: soil pH 8.75–9.00 and RSC_{iw} 4.5–5.5 me L^{-1}; SS5: soil pH 9.00–9.25 and RSC_{iw} 5.5–6.5 me L^{-1}; SS6: soil pH ≥ 9.25 and RSC_{iw} ≥ 6.5 me L^{-1}. Data are mean value of 54 pooled measurements values with different superscript (A–F) letters across sodicity stress (within row) and varieties (within column) show the significant difference at p = 0.05 according to least significant difference test for separation of mean. data followed by different superscript letters across sodicity stress (within row) and varieties (within column) differ significantly ($p \leq 0.05$) using least significant difference test.

Table 3. Preference score of variety traits in wheat.

Variables	Preference Score * (Mean ± SE)	
	KRL 210	HD 2967
Biomass production	4.28 ± 0.45	4.40 ± 0.50
Tillering capacity	3.58 ± 0.50	3.35 ± 0.48
Sodicity tolerance	4.15 ± 0.39	3.50 ± 0.51
Lodging score	4.78 ± 0.42	4.08 ± 0.35
Disease resistance	4.13 ± 0.61	4.18 ± 0.71
Grain boldness	3.78 ± 0.59	3.98 ± 0.35
Grain quality	4.35 ± 0.48	4.13 ± 0.33
Maturity duration	4.73 ± 0.45	4.45 ± 0.50
Profitability	3.75 ± 0.48	3.63 ± 0.49
Grain yield (t ha^{-1})	4.09 ± 0.46	3.91 ± 0.55
Preference score	0.20	0.17

* Preference Scale (1–5), 1: least preferred; 5: most preferred.

3.2. Correlation Studies

Results of correlation analysis indicated that physiological traits were either positively or negatively associated between themselves and with yield traits (Figure 3). MII had a significant negative correlation with gas exchange traits viz. with Pn (r = −0.82), gS (r = −0.87), and E (r = −0.79); however, a significant positive association with P (r = 0.88), NaK_S (r = 0.92), and NaK_R (r = 0.90) (Supplementary Table S3). In contrast, moderate to high positive correlation was seen between physiological traits (Pn, gS, and E) and RWC ($r \geq 0.85$); traits strongly associated with enhanced physiological and agronomic efficiency of growing plants. Moderate to high positive relationships was observed between yield attributing traits with RWC (r = 0.66–0.88), Pn (r = 0.59–0.80), gS (r = 0.55–0.82) and E (r = 0.51–0.79). A strong positive association among yield–related traits (Figure 3) directly influenced the wheat yield (ET, r = 0.84; GE, r = 0.90; and GW, r = 0.76) under sodic conditions.

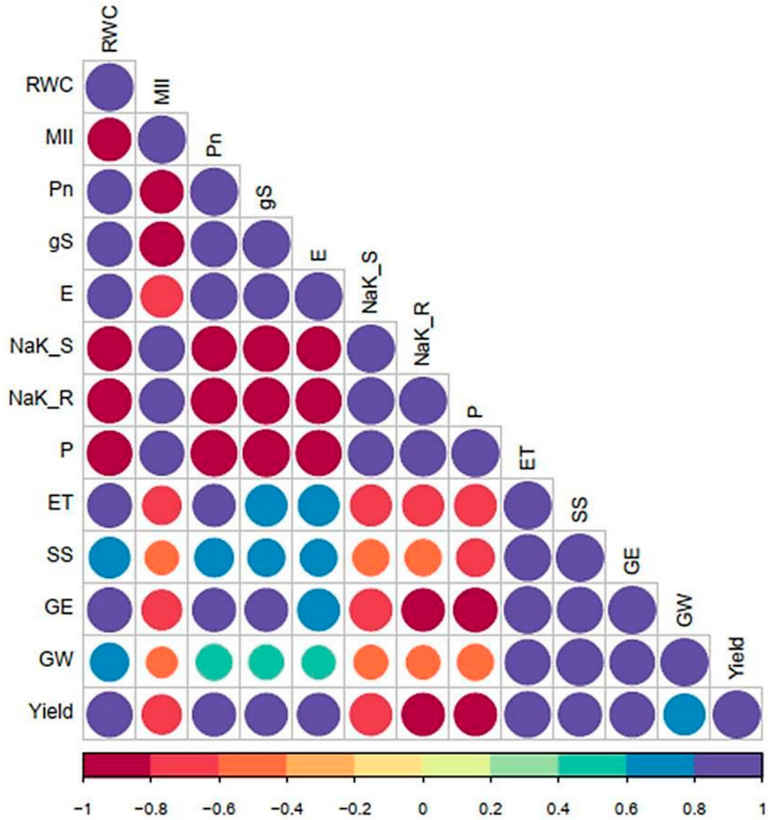

Figure 3. Pearson's correlation coefficients between physiological and yield-related traits of wheat varieties grown on RSC_{iw} irrigated sodic soils. The color and size of the circle reflect the strength of the correlation. The correlation coefficients represent mean value of 54 pooled measurements. RWC: Relative water content; MII: Membrane injury index; Pn; Photosynthetic rate; gS: Stomatal conductance; E: Transpiration rate; NaK_S: Na^+/K^+ ratio in shoot; NaK_R: Na^+/K^+ ratio in root; P: Proline: ET: Effective tillers; SS: Spikelets spike^{-1}; GE: Grains earhead^{-1}; GW: 1000-grain weight.

3.3. Farmers' Preference and Trait Analysis

Data on preference analysis as a selection criterion revealed differences in evaluated traits for the examined varieties; as evident by positive correlations between preference scores of male and female farmers (r = 0.86 **) and between farmers and researchers (r = 0.71 *). Most farmers showed a clear preference for KRL 210 because of its (i) environmental adaptability (sodicity tolerance; score: 4.15 ± 0.39), (ii) productive tillering capability (score: 3.58 ± 0.50), (iii) less lodging (score: 4.78 ± 0.42) whenever water stagnation occurs either due to intense rainfall or an irrigation event, and (iv) shorter crop cycle (5–7 days earliness) (Table 3). Moreover, environmental adaptability and shorter duration of this variety not only contributes to better factor productivity and yield stability under sodic farm situations, but also provides compensation for damage caused by terminal heat stress. Women farmers selected KRL 210 because of good taste and grain quality (score: 4.35 ± 0.48) of food preparations.

3.4. Dissection of Salt Tolerance and Yield Assessments (FPT–II)

To further validate the experimental findings, the yield data estimated over a broad range of sodicity stress (soil pH and RSC_{iw}) was dissected to quantify the relative crop response and changes in wheat yield. Scatter diagram plotted for mean grain yield harvested over 308 on-farm locations in response to variable soil sodicity (Figure 4) and irrigation water residual alkalinity (Figure 5) revealed that both the varieties intersected each other at soil pH~8.6 and RSC_{iw} ~3.3 me L^{-1}. It is interesting to note that HD 2967 attained significantly ($p \leq 0.05$) higher grain yield than KRL 210 up to soil pH ≤ 8.2 and $RSC_{iw} \leq 2.5$ me L^{-1}, thereafter, both the varieties were equally competitive and produced similar crop yields at soil pH between 8.2 and 8.7 and RSC_{iw} between 2.5 and 4.0 me L^{-1}. The yield gap between the two varieties continued to widen with significantly better ($p \leq 0.05$) performance of KRL 210 relative to HD 2967 at soil pH > 8.7 and RSC_{iw} > 4 me L^{-1} and so on; confirming the higher tolerance of KRL 210 with increasing sodicity stress (Figures 4 and 5; Supplementary Tables S4 and S5).

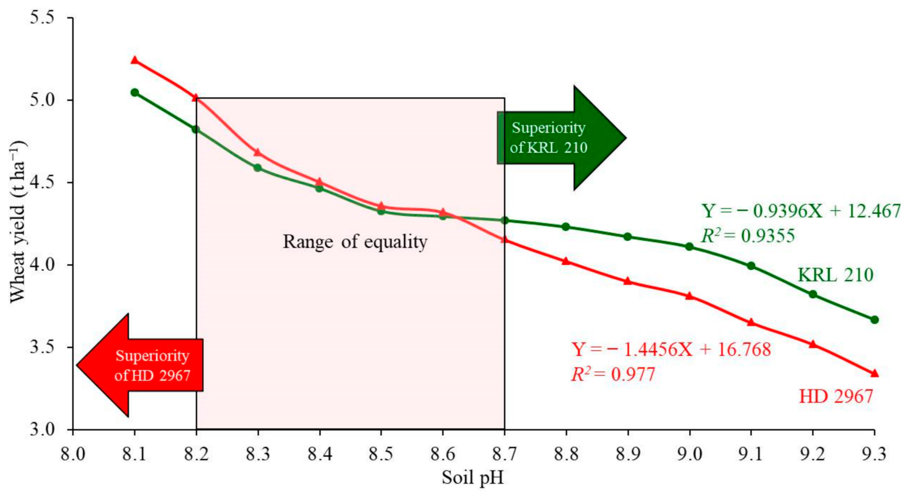

Figure 4. Quantitative dissection showing yield reduction for two wheat varieties (KRL 210 and HD 2967) in relation to variable soil sodicity (soil pH) at farmers' fields.

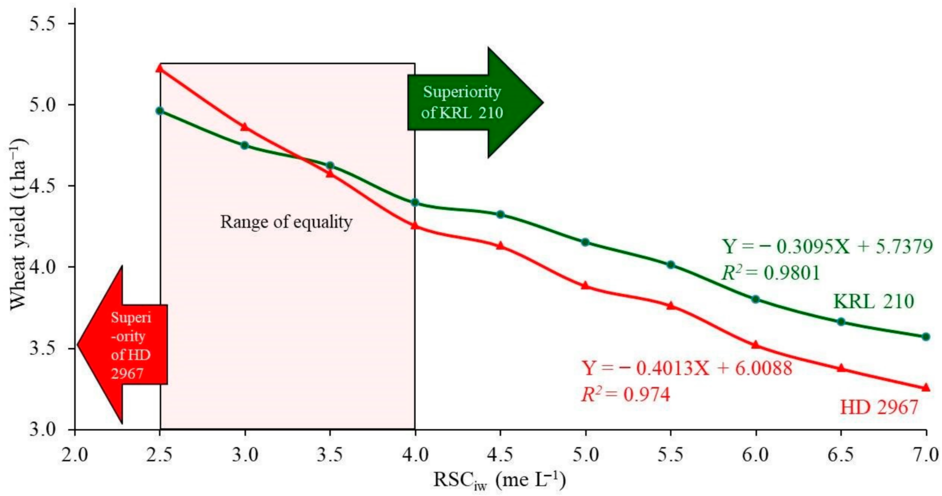

Figure 5. Quantitative dissection showing yield reduction for two wheat varieties (KRL 210 and HD 2967) in relation to irrigation water alkalinity (RSC_{iw}) at farmers' fields.

Furthermore, the confidence interval of the regression coefficients revealed that for each unit increase in soil pH; yield reduction to the tune of 0.77–1.10 t ha^{-1} in KRL 210 was observed as against 1.30–1.59 t ha^{-1} in HD 2967 (Table 4). The corresponding yield reduction remained 0.29–0.33 t ha^{-1} in KRL 210 and 0.37–0.48 t ha^{-1} in HD 2967 for each unit increase in RSC_{iw}.

Table 4. Response equation for wheat yield prediction in response to soil sodicity and irrigation water residual alkalinity (FPT–II).

Variety	Equation	R^2 Value	Per Unit Reduction in Yield at 95% CI	Validation Limits
		Soil pH		
KRL 210	Y = −0.939X + 12.467	0.93	0.77–1.10 t ha^{-1}	7.8–9.3
HD 2967	Y = −1.446X + 16.768	0.98	1.30–1.59 t ha^{-1}	
		Irrigation water residual alkalinity (RSC_{iw})		
KRL 210	Y = −0.3095X + 5.737	0.98	0.29–0.33 t ha^{-1}	1.7–7.5
HD 2967	Y = −0.4103X + 6.008	0.97	0.37–0.48 t ha^{-1}	

4. Discussion

The intergenic variations for salt tolerance within crops and/or plant species is the key to ensure future agricultural growth and economic development in salt-affected regions [11,37]. Plants tend to overcome sodicity-induced injury through certain morphological and anatomical adjustments [38], reduced uptake of toxic Na^+ ions [39], and by regulating organic osmolytes like proline [40]. However, the soil–water–environmental interactions influences the plant's capability to adjust the ambient root zone salinity and sodicity [41–44]; and therefore, predicts the relative crop response and concomitant yield reductions in response to known salt stress [45,46].

In the present study, long-term use of bicarbonate ($NaHCO_3^-$) rich irrigation water in a rice–wheat cropping system increased the sodium saturation in the surface layer over time depending on the seasonal water use and rainfall received (Figure 2). RSC_{iw} induced soil sodification ascertained significant ($p \leq 0.05$) changes in all the plant physiological (Table 2) and agronomic traits (Table 3) regardless of the cultivated varieties (KRL 210 and HD 2967). However, the quantum of response varied in accordance with their relative tolerance and plant adjustments to prevalent stress conditions. Our findings suggests better physiological and biochemical adaptation of salt tolerant KRL 210 to the ambient sodicity stress (Table 1); maintaining relatively higher mean plant water relations (RWC, 1.9%) and lower stress injury (MII, −8.5%) on mean basis. This favorable water balance equilibrium and membrane stability in KRL 210 allowed the growing plants to sustain higher leaf gas exchange; 5.1% higher net photosynthesis (Pn), 6.6% higher stomatal conductance (gS) and 4.1% higher transpiration rate (E). These conditions together helped in managing an improved ion balance (NaK_S; −23.1% and NaK_R; −18.7%) and showed better control on accumulation of free proline (P; −18.4%) in the plant tissues. In contrast, the increased accumulation of salt ions (30% higher NaK_S and 23% higher NaK_R) and dehydrated plant tissues (9.3% higher MII) in HD 2967 induced decrease in accumulation and transport of assimilation products and metabolic impairments, thereby, negatively affecting the photosynthetic efficiency (Table 1) [47,48]. Sodicity induced photosynthetic decline in HD 2967 coincided with a significant decrease in stomatal conductance (gS; −6.2%) and transpiration rate (E; −3.9%). Salt (Na^+) accumulation in the plant tissues enhances the accumulation of reactive oxygen species (ROS), damages the cellular membranes, and affects the bioenergetic activities [49–51]. Such structural and functional changes induces ionic or osmotic stress to growing plants by increasing the plasma membrane permeability and electrolyte leakage [52,53], thereby affecting the plant salt tolerance and adaptation capacity. Experimental evidences also highlighted the relevance of salt tolerance mechanisms by modulating assimilates translocation to the aerial plant portions [54], maintaining improved ion balance [55], and by accumulating osmoprotectants to safeguard the cellular components from ROS [56,57]. Munns et al. [58] also observed Na^+ discrimination and K^+ preferential uptake in tolerant varieties compared to susceptible ones.

Altered physiological response suppressed important yield-related traits; revealing repressive effects of sodicity stress on wheat yields (Table 2). A strong positive association of important physiological parameters of crop growth with yield-related traits; directly or indirectly influenced the wheat yield under stress conditions (Figure 3). Across varieties, low grain yields with increasing sodicity stress were presumably due to imbalanced source to sink ratio, dispersed soil conditions, physiological and nutritional imbalances, reduced enzymatic and metabolic activities, and an increase in soil pH and ESP [6,12]. These soil conditions adversely affected the physiological (reduced photosynthesis, stomatal limitation and metabolic impairment) and agronomic efficiency (poor tillers, higher sterility, unhealthy grains) of growing plants [49,59,60]. Within varieties, better physiological adaptation of salt tolerant KRL 210 witnessed lesser reduction in effective tillers (3.4%) and grains earhead^{-1} (4.6%), culminating in ~5% yield advantage over the locally adapted HD 2967 (Table 2). In addition, the farmers also preferred salt tolerant KRL 210 as remunerative one in terms of early maturity (5–7 days earliness), lodging resistance, higher per day productivity and good chapatti quality with better adaptation to prolonged water stagnation following rainfall or irrigation events under sodic conditions (Table 3). Similar results on better plant salt tolerance, environmental adaptability and associated higher crop yields in stress tolerant genotypes have been stated by Ismail and Horie [22]; Ahanger et al. [61]; Iqbal et al. [62]; and Monneveux et al. [63].

Multiple interaction of farm (land, water, and crop) based management practices most likely decide the relevance of any demonstrated technology [64,65]. The crop performance quantified over 308 locations representing diverse farm situations revealed that concomitant increase in soil sodicity (soil pH) and deteriorating water quality (RSC_{iw}) negatively impacted the wheat yields; albeit to a greater extent in HD 2967 (Figures 4 and 5). Traditionally cultivated HD 2967 significantly ($p \leq 0.05$) outyielded KRL 210 in fields having soil pH $\leq$ 8.2 and irrigated with $RSC_{iw} \leq 2.5$ me L^{-1}. By comparison, the crop performance of salt tolerant KRL 210 was found significantly better at soil pH > 8.7 and $RSC_{iw} > 4$ me L^{-1}. Overall, the yield reduction with increasing sodicity stress from SS1 to SS6 was 23% in KRL 210 and 30% in HD 2967 with an average decline of 27% across varieties (Table 1). At the same level of sodicity stress, the yield reduction with each gradual increase in soil pH and RSC_{iw} was comparatively less in case of KRL 210 compared to its counterpart HD 2967 (Supplementary Tables S3 and S4). These results supports the earlier findings demonstrating better environmental adaptability and obtaining stable yields for tolerant varieties in stress prone areas [66]. Further, synergy of adaptive (better plant salt tolerance) and mitigation (low-cost reclamation methods) strategies have shown tremendous potential in closing the yield gaps, halting salt-induced land degradation and improving rural livelihood in situations where sodic soils exist and are irrigated with poor quality water [11]. The critical limits of sodicity (soil and water) tolerance so defined will broaden the farmers' choice in suitable variety selection to bridge the yield gaps under their local farm situations.

5. Conclusions

This study highlights the need for considering farmers' knowledge and their engagement in testing and validation of any specific recommendations to ensure large-scale adoption. Compared to traditionally grown HD 2967, better plant morpho-physiological adjustments and lesser yield reduction with increasing sodicity stress in KRL 210 offered better opportunity to harness the potential of sodic soils irrigated with alkali water. Defining the critical limits of sodicity tolerance will help address the farmers' acceptance and importance of selecting suitable variety to enhance crop resilience, stabilize production, and generate higher income under the existing or predicted levels of sodicity stress. The information contained herein will certainly help generating useful insights for convincing the developmental agencies and receive government attention while formulating the policy guidelines for wheat developmental program in salt-affected ecologies.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/6/3378/s1, Figure S1: Maps showing the extent and distribution of available N, P, K and Zn status in the study area., Table S1: Field locations, initial soil and irrigation water quality status of selected sites (FPT–I), Table S2: Farmers' perception towards wheat management practices in sodicity affected areas, Table S3: Pearson correlation (*r*) between important physiological and yield–related traits of wheat grown on RSC water irrigated sodic soils, Table S4: Test of significance of wheat varieties (KRL 210 and HD 2967) in response to variable soil sodicity (FPT–II), Table S5: Test of significance of wheat varieties (KRL 210 and HD 2967) irrigated with water having residual alkalinity (FPT–II).

Author Contributions: Conceptualization, P.C.S., R.K.Y., P.S. and V.P.C.; methodology, P.S. and R.S.; software, A.K. (Arvind Kumar); validation, R.S., R.R., A.B. and S.K.S.; formal analysis, K.P. and Y.J.D.; investigation, P.S., R.S. and A.K. (Ashwani Kumar); resources, P.S. and P.C.S.; data curation, K.P. and R.S.; writing—original draft preparation, P.S. and A.K. (Arvind Kumar); writing—review and editing, R.K.Y., P.C.S., R.K.S. and S.K.; visualization, R.S., A.B. and P.S.; supervision, P.S. and P.C.S.; project administration, P.C.S. and P.S.; funding acquisition, R.K.Y., P.S. and P.C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Indian Council of Agricultural Research (ICAR), New Delhi under Farmer FIRST Project operated at ICAR–Central Soil Salinity Research Institute (CSSRI), Karnal (Project Code: NRMACSSRISOL2016026000924).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors sincerely acknowledge and thank the Indian Council of Agricultural Research (ICAR), New Delhi for providing the financial support to implement the Farmer FIRST Project in participatory mode. We also acknowledge the wholehearted support of all the participating farmers for giving opportunity to conduct these on–farm trials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ait-Mouheb, N.; Bahri, A.; Thayer, B.B.; Benyahia, B.; Bourrie, G.; Cherki, B.; Kitir, N. The reuse of reclaimed water for irrigation around the Mediterranean Rim: A step towards a more virtuous cycle? *Reg. Environ. Chang.* **2018**, *18*, 693–705. [CrossRef]
2. Angelakıs, A.N.; Zaccaria, D.; Krasilnikoff, J.; Salgot, M.; Bazza, M.; Roccaro, P.; Jimenez, B.; Kumar, A.; Yinghua, W.; Baba, A.; et al. Irrigation of World Agricultural Lands: Evolution through the Millennia. *Water* **2020**, *12*, 1285. [CrossRef]
3. Jury, W.A.; Vaux, H.J., Jr. The emerging global water crisis: Managing scarcity and conflict between water users. *Adv. Agron.* **2007**, *95*, 1–76.
4. Qadir, M.; Sharma, B.R.; Bruggeman, A.; Choukr-Allah, R.; Karajeh, F. Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. *Agric. Water Manag.* **2007**, *87*, 2–22. [CrossRef]
5. Shani, U.; Dudley, L.M. Field studies of crop response to water and salt stress. *Soil Sci. Soc. Am. J.* **2001**, *65*, 1522–1528. [CrossRef]
6. Minhas, P.S.; Qadir, M.; Yadav, R.K. Groundwater irrigation induced soil sodification and response options. *Agric. Water Manag.* **2019**, *215*, 74–85. [CrossRef]
7. Bartels, D.; Sunkar, R. Drought and salt tolerance in plants. *Crit. Rev. Plant Sci.* **2005**, *24*, 23–58. [CrossRef]
8. Sharma, D.K.; Thimmappa, K.; Chinchmalatpure, A.R.; Mandal, A.K.; Yadav, R.K.; Chaudhari, S.K.; Kumar, S.; Sikka, A.K. *Assessment of Production and Monetary Losses from Salt Affected Soils in India*; Technical Bulletin; ICAR-CSSRI: Karnal, India, 2015; pp. 1–99.
9. Singh, Y.P.; Mishra, V.K.; Singh, S.; Sharma, D.K.; Singh, D.; Singh, U.S.; Singh, R.K.; Haefele, S.M.; Ismail, A.M. Productivity of sodic soils can be enhanced through the use of salt tolerant rice varieties and proper agronomic practices. *Field Crops Res.* **2016**, *190*, 82–90. [CrossRef] [PubMed]
10. Minhas, P.S.; Bali, A.; Bhardwaj, A.K.; Singh, A.; Yadav, R.K. Structural stability and hydraulic characteristics of soils irrigated for two decades with water having residual alkalinity and its neutralization with gypsum and sulphuric acid. *Agric. Water Manag.* **2021**, *244*, 106609. [CrossRef]
11. Sheoran, P.; Basak, N.; Kumar, A.; Yadav, R.K.; Singh, R.; Sharma, R.; Kumar, S.; Singh, R.K.; Sharma, P.C. Ameliorants and salt tolerant varieties improve rice-wheat production in soils undergoing sodification with alkali water irrigation in Indo–Gangetic Plains of India. *Agric. Water Manag.* **2021**, *243*, 106492. [CrossRef]
12. Choudhary, O.P.; Ghuman, B.S.; Thuy, N.; Buresh, R.J. Effects of long-term use of sodic water irrigation, amendments and crop residues on soil properties and crop yields in rice–wheat cropping system in a calcareous soil. *Field Crops Res.* **2011**, *121*, 363–372. [CrossRef]
13. Murtaza, G.; Ghafoor, A.; Qadir, M. Irrigation and soil management strategies for using saline-sodic water in a cotton–wheat rotation. *Agric. Water Manag.* **2006**, *81*, 98–114. [CrossRef]

14. Bagarello, V.; Iovino, M.; Palazzolo, E.; Panno, M.; Reynolds, W.D. Field and laboratory approaches for determining sodicity effects on saturated soil hydraulic conductivity. *Geoderma* **2006**, *130*, 1–13. [CrossRef]
15. Shaw, R.J.; Coughlin, K.J.; Bell, L.C. Root zone sodicity. In *Distribution, Management and Environmental Consequences*; Oxford University Press: New York, NY, USA, 1998; pp. 95–106.
16. Arif, Y.; Singh, P.; Siddiqui, H.; Bajguz, A.; Hayat, S. Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. *Plant Physiol. Biochem.* **2020**, *156*, 64–77. [CrossRef] [PubMed]
17. Sharma, D.K.; Singh, A.; Sharma, P.C.; Dagar, J.C.; Chaudhari, S.K. Sustainable management of sodic soils for crop production: Opportunities and challenges. *J. Soil Salin. Water Qual.* **2016**, *8*, 109–130.
18. Machado, R.; Serralheiro, R. Soil Salinity: Effect on vegetable crop growth management practices to prevent and mitigate soil salinization. *Horticulturae* **2017**, *3*, 30. [CrossRef]
19. Qadir, M.; Oster, J.D. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Sci. Total Environ.* **2004**, *323*, 1–19. [CrossRef]
20. Sheoran, P.; Kumar, A.; Kumar, A.; Raju, R.; Sharma, R.; Parjapat, K.; Barman, A.; Singh, R.K.; Kumar, S.; Sharma, P.C.; et al. Impact of pressmud application in reclamation of high RSC irrigation water induced soil sodification and sustaining rice (*Oryza sativa*)–wheat (*Triticum aestivum*) production in Indo-Gangetic Plains. *Indian J. Agric. Sci.* **2020**, *90*, 206–211.
21. Hammer, G.L.; Broad, I.J. Genotype and environment effects on dynamics of harvest index during grain filling sorghum. *Agron. J.* **2003**, *95*, 199–206. [CrossRef]
22. Ismail, A.M.; Horie, M. Genomics, physiology, and molecular breeding approaches for improving salt tolerance. *Ann. Rev. Plant Biol.* **2017**, *68*, 405–434. [CrossRef]
23. Rhoades, J.D. Intercepting, isolating and reusing drainage water for irrigation to conserve water and protect water quality. *Agric. Water Manag.* **1989**, *16*, 37–52. [CrossRef]
24. FAO. Characterization of Small Farmers in Asia and the Pacific. Asia and Pacific Commission on Agricultural Statistics: Twenty Third Sessions. Siem Reap, Cambodia. 2010. Available online: http://www.fao.org/fileadmin/templates/ess/documents/meetings_and_workshops/APCAS23/documents_OCT10/APCAS-10-28_-Small_farmers.pdf (accessed on 15 March 2020).
25. Richards, L.A. *Diagnosis and Improvement of Saline and Alkali Soils. USDA Handbook No. 60*; Oxford & IBH Publishing Co.: New Delhi, India, 1954.
26. Page, A.L.; Miller, R.H.; Keeney, D.R. *Methods of Soil Analysis, Part-2*, 2nd ed.; Soil Science Society of America: Madison, WI, USA, 1982.
27. Subbiah, B.V.; Asija, G.L. A rapid procedure for the determination of available nitrogen in soils. *Curr. Sci.* **1956**, *25*, 259–260.
28. Olsen, S.R.; Col, C.W.; Watanabe, F.S.; Dean, L.A. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*; USDA: Washington, DC, USA, 1954.
29. Hanway, J.J.; Heidel, H. Soil analysis methods as used in Iowa State College, Soil Testing Laboratory. *Iowa Agric.* **1952**, *54*, 1–31.
30. Mandal, A.K. Mapping and characterization of salt-affected and waterlogged soils in the Gangetic plain of central Haryana (India) for reclamation and management. *Cogent Geosci.* **2016**, *2*, 1213689. [CrossRef]
31. Minhas, P.S.; Gupta, R.K. *Quality of Irrigation Water: Assessment and Management*; Indian Council of Agricultural Research: New Delhi, India, 1992; p. 123.
32. Weatherley, P.E. Studies in the water relations of the cotton plant. I. The field measurement of water deficits in leaves. *New Phytol.* **1950**, *49*, 81–87. [CrossRef]
33. Dionisio-Sese, M.L.; Tobita, S. Effects of salinity on sodium content and photosynthetic responses of rice seedlings differing in salt tolerance. *J. Plant Physiol.* **2000**, *157*, 54–58. [CrossRef]
34. Bates, L.S.; Waldren, R.P.; Teare, I.D. Rapid determination of free proline for water-stress studies. *Plant Soil* **1973**, *39*, 205–207. [CrossRef]
35. AOAC. *Official Methods of Analysis of the AOAC*, 15th ed.; Association of Official Analytical Chemists: Arlington, VA, USA, 1990.
36. Shapiro, S.S.; Wilk, M.B. An analysis of variance test for normality (complete samples). *Biometrika* **1965**, *52*, 591–611. [CrossRef]
37. Qadir, M.; Tubeileh, A.; Akhtar, J.; Larbi, A.; Minhas, P.S.; Khan, M.A. Productivity enhancement of salt-affected environments through crop diversification. *Land Degrad. Dev.* **2008**, *19*, 429–453. [CrossRef]
38. De Souza, E.R.; dos Santos Freire, M.B.G.; da Cunha, K.P.V.; do Nascimento, C.W.A.; Ruiz, H.A.; Lins, C.M.T. Biomass, anatomical changes and osmotic potential in *Atriplex nummularia* Lindl. cultivated in sodic saline soil under water stress. *Environ. Expt. Bot.* **2012**, *82*, 20–27. [CrossRef]
39. Saqib, M.; Zörb, C.; Schubert, S. Silicon-mediated improvement in the salt resistance of wheat (*Triticum aestivum*) results from increased sodium exclusion and resistance to oxidative stress. *Funct. Plant Biol.* **2008**, *35*, 633–639. [CrossRef]
40. Lutts, S.; Majerus, V.; Kinet, J.M. NaCl effects on proline metabolism in rice (*Oryza sativa*) seedlings. *Physiol. Plant.* **1999**, *105*, 450–458. [CrossRef]
41. Maas, E.V.; Hoffman, G.J.; Chaba, G.D.; Poss, J.A.; Shannon, M.C. Salt sensitivity of corn at various growth stages. *Irrig. Sci.* **1983**, *4*, 45–57. [CrossRef]
42. Koyama, M.L.; Levesley, A.; Koebner, R.M.; Flowers, T.J.; Yeo, A.R. Quantitative trait loci for component physiological traits determining salt tolerance in rice. *Plant Physiol.* **2001**, *125*, 406–422. [CrossRef]
43. Hussain, S.; Zhang, J.H.; Zhong, C.; Zhu, L.F.; Cao, X.C.; Yu, S.M.; James, A.B.; Hu, J.J.; Jin, Q.Y. Effects of salt stress on rice growth, development characteristics, and the regulating ways: A review. *J. Integr. Agric.* **2017**, *16*, 2357–2374. [CrossRef]

44. Qadir, M.; Oster, J.D. Vegetative bioremediation of calcareous sodic soils: History, mechanisms, and evaluation. *Irrig. Sci.* **2002**, *21*, 91–101.
45. Maas, E.V. Plant growth response to salt stress. In *Towards the Rational Use of High Salinity Tolerant Plants*; Springer: Dordrecht, The Netherlands, 1993; pp. 279–291.
46. Van Straten, G.; de Vos, A.C.; Rozema, J.; Bruning, B.; van Bodegom, P.M. An improved methodology to evaluate crop salt tolerance from field trials. *Agric. Water Manag.* **2019**, *213*, 375–387. [CrossRef]
47. Vysotskaya, L.; Hedley, P.E.; Sharipova, G.; Veselov, D.; Kudoyarova, G.; Morris, J.; Jones, H.G. Effect of salinity on water relations of wild barley plants differing in salt tolerance. *Acta Plants* **2010**, plq006. [CrossRef]
48. Saqib, M.; Akhtar, J.; Abbas, G.; Nasim, M. Salinity and drought interaction in wheat (*Triticum aestivum* L.) is affected by the genotype and plant growth stage. *Acta Physiol. Plant.* **2013**, *35*, 2761–2768. [CrossRef]
49. Munns, R. Comparative physiology of salt and water stress. *Plant Cell Environ.* **2002**, *25*, 239–250. [CrossRef]
50. Sudhir, P.; Murthy, S.D.S. Effects of salt stress on basic processes of photosynthesis. *Photosynthetica* **2004**, *42*, 481–486. [CrossRef]
51. Zhang, M.; Smith, J.A.C.; Harberd, N.P.; Jiang, C. The regulatory roles of ethylene and reactive oxygen species (ROS) in plant salt stress responses. *Plant Mol. Biol.* **2016**, *91*, 651–659. [CrossRef]
52. Demidchik, V.; Straltsova, D.; Medvedev, S.S.; Pozhvanov, G.A.; Sokolik, A.; Yurin, V. Stress-induced electrolyte leakage: The role of K^+-permeable channels and involvement in programmed cell death and metabolic adjustment. *J. Exp. Bot.* **2014**, *65*, 1259–1270. [CrossRef]
53. Mansour, M.M.F. Plasma membrane permeability as an indicator of salt tolerance in plants. *Biol. Plant.* **2013**, *57*, 1–10. [CrossRef]
54. Dadshani, S.; Sharma, R.C.; Baum, M.; Ogbonnaya, F.C.; Le'on, J.; Ballvora, A. Multidimensional evaluation of response to salt stress in wheat. *PLoS ONE* **2019**, *14*, e0222659. [CrossRef]
55. El-Hendawy, S.; Hassan, W.M.; Al-Suhaibani, N.A.; Refay, Y.; Abdella, K.A. Comparative performance of multivariable agro-physiological parameters for detecting salt tolerance of wheat cultivars under simulated saline field growing conditions. *Front. Plant Sci.* **2017**, *8*, 435. [CrossRef] [PubMed]
56. Chunthaburee, S.; Dongsansuk, A.; Sanitchon, J.; Pattanagul, W.; Theerakulpisut, P. Physiological and biochemical parameters for evaluation and clustering of rice cultivars differing in salt tolerance at seedling stage. *Saudi J. Biol. Sci.* **2016**, *23*, 467–477. [CrossRef] [PubMed]
57. Mann, A.; Kumar, A.; Saha, M.; Lata, C.; Kumar, A. Stress induced changes in osmoprotectants, ionic relations, antioxidants activities and protein profilling characterize *Sporobolus marginatus* Hochst. Ex A. Rich. Salt tolerance mechanism. *Indian J. Expt. Biol.* **2019**, *57*, 672–679.
58. Munns, R.; James, R.A.; Lauchli, A. Approaches to increasing the salt tolerance of wheat and other cereals. *J. Expt. Bot.* **2006**, *57*, 1025–1043. [CrossRef]
59. Tavakkoli, E.; Fatehi, F.; Coventry, S.; Rengasamy, P.; McDonald, G.K. Additive effects of Na and Cl–ions on barley growth under salinity stress. *J. Exp. Bot.* **2011**, *62*, 2189–2203. [CrossRef] [PubMed]
60. Hajiboland, R.; Norouzi, F.; Poschenrieder, C. Growth, physiological, biochemical and ionic responses of pistachio seedlings to mild and high salinity. *Trees* **2014**, *28*, 1065–1078. [CrossRef]
61. Ahanger, M.A.; Tomar, N.S.; Tittal, M.; Argal, S.; Agarwal, R.M. Plant growth under water/salt stress: ROS production; antioxidants and significance of added potassium under such conditions. *Physiol. Mol. Biol. Plants* **2017**, *23*, 731–744. [CrossRef] [PubMed]
62. Iqbal, M.M.; Murtaza, G.; Saqib, Z.A.; Rashid, A. Growth and physiological responses of two rice varieties to applied lead in normal and salt-affected soils. *Int. J. Agric. Biol.* **2015**, *17*, 901–910. [CrossRef]
63. Monneveux, P.; Rekika, D.; Acevedo, E.; Merah, O. Effect of drought on leaf gas exchange, carbon isotope discrimination, transpiration efficiency and productivity in field grown durum wheat genotypes. *Plant Sci.* **2006**, *170*, 867–872. [CrossRef]
64. Liu, T.; Bruins, R.J.; Heberling, M.T. Factors influencing farmers' adoption of best management practices: A review and synthesis. *Sustainability* **2018**, *10*, 432. [CrossRef] [PubMed]
65. Shah, F.; Wu, W. Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability* **2019**, *11*, 1485. [CrossRef]
66. Nikam, V.R.; Singh, R.K.; Chinchmalatpure, A. Salt tolerant varieties: A biological intervention to manage saline and sodic environment and sustain livelihoods. *J. Soil Salin. Water Qual.* **2016**, *8*, 37–44.