Journal of Soil Salinity and Water Quality 18(1), 31-38, 2026
DOI: https://doi.org/10.56093/jsswq.v18i1.173823

Enhancing Productivity of Saline-Sodic Soils through Conservation Agriculture: An On-Farm Study in Rice-Wheat System

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Abstract

Salinity and sodicity severely limit the productivity of the rice-wheat system (RWS) in the Indo-Gangetic Plains. Conservation Agriculture (CA) practices offer potential to restore soil health and sustain yields under such constraints. A five-year (2015–2020) on-farm study was conducted at four sites in Haryana, namely Geong, Sambhli, Bhaupur and Kaith, under varying saline and sodic environments. Four management scenarios (SCs) combining tillage, residue, and irrigation were evaluated namely: (Sc-1) puddled transplanted rice – conventional tillage wheat (conventional farmer's practice; PTR–CTW), (Sc-2) PTR + wheat residue incorporation – CTW + rice residue mulch, (Sc-3) reduce tillage direct seeded rice (RTDSR) + wheat residue incorporation – zero-tillage wheat (ZTW) + rice residue mulch under surface irrigation, and (Sc-4) RTDSR + wheat residue incorporation – ZTW + rice residue mulch under sprinkler irrigation. The salt-tolerant varieties Basmati CSR 30 (rice) and KRL 210 (wheat) were used as test crop. Pooled analysis revealed that sprinkler-based RTDSR–ZTW with residue retention achieved the highest system productivity (9.6 Mg ha^{-1} yr^{-1}), outperforming the conventional practice by 15–18%. Rice and wheat yields increased by 11 and 17.8%, respectively. The findings suggest that CA-based irrigation and residue management strategies can be up-scaled through national soil health and land degradation neutrality programmes to ensure the sustainability of RWS. However, the study was limited by the absence of detailed measurements on exchangeable sodium percentage and hydraulic conductivity, which warrant future investigation.

Keywords: Saline-sodic soils, Conservation agriculture, Sprinkler irrigation, Rice–wheat system

Introduction

Rice–wheat system (RWS) in the Indo-Gangetic Plains (IGP) is the backbone of India's food security, contributing significantly to the national production of rice and wheat. However, intensive tillage, rice puddling, inefficient water use, residue burning, and continuous monoculture have degraded soil health, lowered the groundwater table, and reduced productivity (Ladha *et al.,* 2007). In many parts of IGP, especially Haryana, Punjab, and Uttar Pradesh, declining groundwater levels, deteriorating irrigation water quality, and increasing area of salt affected soils are adding to the challenge (Kumar and Sharma, 2020). Salt affected soils are a major constraint in India. About 6.73 million ha (Mha) of land in India are salt-affected, of which ~3.78 Mha are sodic and ~2.96 Mha are saline (Fagodiya *et al.,* 2022). In the IGP alone, approximately 2.35 Mha salt affected soils occur, including 1.79 Mha sodic soils (Kumar and Sharma, 2020). These areas often experience poor infiltration, degraded soil structure, low crop productivity, and constraints in the adoption of improved practices. Reclamation has been attempted through chemical amendments (gypsum) and the use of salt-tolerant varieties (Yadav *et al.,* 2023).

Conservation agriculture (CA) practices, including reduced/zero tillage, retention of crop residue, efficient irrigation, and crop rotation, are recognised as a promising approach to restore soil health, enhance moisture retention, reduce energy input, and improve yields under stress environments (Jat *et al.,* 2020; 2024). In RWS, practices like direct seeded rice (DSR) and zero tillage wheat (ZTW) with residue retention have shown potential to reduce water use, prevent soil structural damage from puddling, increase organic carbon, and maintain yield levels (Singh *et al.,* 2022; Fagodiya *et al.,* 2024a,b). At ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, several best practices have been developed and tested for RWS under CA. For example, use of mini-sprinkler irrigation in DSR with wheat residue incorporation (SPRL-DSR+RI) has been shown to save irrigation water, increase water productivity, reduce food-water-energy footprints and maintain yield in trials (Fagodiya *et al.,* 2023; Jatana *et al.,* 2025). The ZTW with rice residue mulch under sprinkler irrigation has also shown promise in maintaining soil moisture, enhancing wheat yields, and reducing environmental footprints (Singh *et al.,* 2023).

While many trials have been conducted under experimental station conditions, validation under real farmers' fields in saline/sodic environment is less common. There is limited information on how the bundle of the technological components, i.e., reduce tillage DSR and ZTW system with residue incorporation/retention under surface and sprinkler irrigation, performs in salt-affected soils with poor-quality water irrigation. Therefore, the present study aims to evaluate the performance of CA-based RWS practices (DSR/ZTW, residue retention, and sprinkler irrigation) across farmers' fields in a salt-affected environment in Haryana with the hypothesis it will improve the soil environment and mitigate the adverse effects of salinity and sodicity, and thereby improve the productivity of the rice-wheat system compared to farmers practice. The objective of the study was to evaluate the yield responses of rice and wheat under different tillage-residue-irrigation management scenarios (SCs) in saline-sodic environment.

Materials and Methods

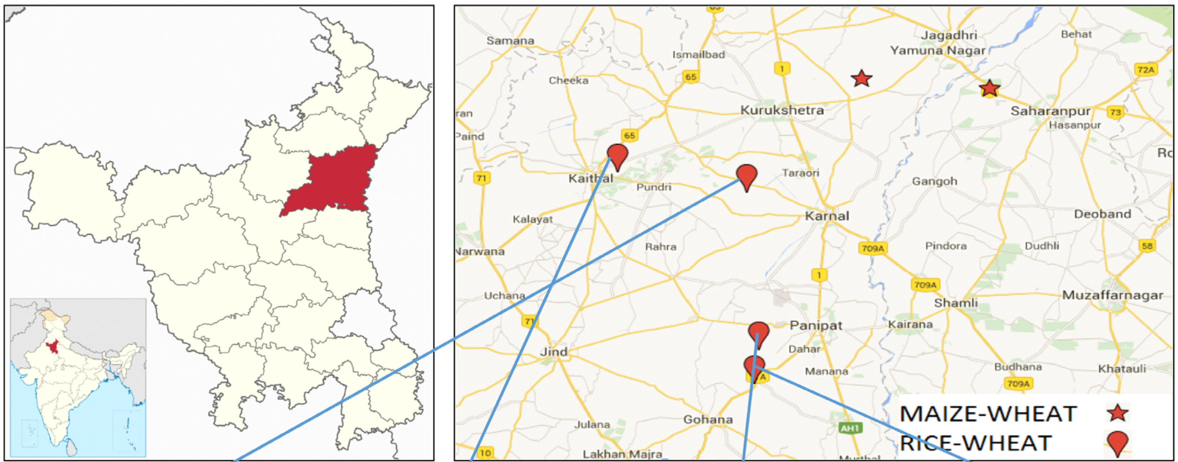
Experimental location and characteristics

The promising CA technologies in the rice–wheat system developed at ICAR–Central Soil Salinity Research Institute, under the Consortia Research Platform (CRP) on CA were evaluated and demonstrated at farmers' fields to validate their performance under real-farm saline/sodic environments. The on-farm demonstrations were conducted from *kharif* 2015 to *rabi* 2020 at four farmers' fields located in different villages namely Geong of Kaithal district, Sambhli of Karnal district, Bhaupur and Kaith of Panipat district in Haryana, India. The quality of irrigation water varied among the villages, being sodic in Geong, saline-sodic in Bhaupur, saline in Kaith, and normal in Sambhali. The locations of these farmers' fields along with the corresponding groundwater quality for irrigation are shown in Fig. 1. The soils of the sites were saline to sodic in nature, with a pH ranging from 8.77 to 9.22 in the 0-15 cm soil layer.

Treatment details and crop management

Each experimental site covered 1 acre (0.4 ha) and was divided into four large plots (~1000 m² each). Each plot represented a treatment, referred to as a scenario, resulting in four combinations that differed in tillage, residue management, and irrigation methods. The four SCs were: (Sc-1) Puddled transplanted rice – conventional tillage wheat (conventional farmer's practice; PTR/CTW); (Sc-2) PTR with one-third wheat residue incorporation – CTW with rice residue mulch/anchored (PTR+RI/CTW+RM); (Sc-3) Reduce tillage direct seeded rice with 1/3rd wheat residue incorporation – zero tillage wheat with rice residue mulch/anchored under surface irrigation (SIS–RTDSR+RI/ZTW+RM); and (Sc-4) RTDSR with 1/3rd wheat residue incorporation –ZTW with rice residue mulch/anchored under sprinkler irrigation (SPRL–RTDSR+RI/ZTW+RM). Details of the treatment SCs are presented in Table 1.

Salt-tolerant crop varieties Basmati CSR 30 (rice) and KRL 210 (wheat) were used for the demonstrations. Rice was established during the *kharif* season (June–November) using Basmati CSR 30. In reduced tillage DSR SCs (Sc-3 and Sc-4), rice was sown during the first fortnight of June with a Turbo Happy Seeder at 25 kg seed ha^{-1}. For comparison with PTR (Sc-1 and Sc-2), nurseries were raised simultaneously using 10 kg seed ha^{-1}, and 25–30-day-old seedlings were transplanted at about 20 cm spacing in puddled



Sambhli (Karnal)		
EC (dS m^{-1})	=	1.06
pH	=	8.13
RSC (me l^{-1})	=	0.90

Geong (Kaithal)		
EC (dS m^{-1})	=	1.32
pH	=	8.66
RSC (me l^{-1})	=	5.2

Bahupur (Panipat)		
EC (dS m^{-1})	=	2.80
pH	=	8.20
RSC (me l^{-1})	=	2.50

Kaith (Panipat)		
EC (dS m^{-1})	=	4.29
pH	=	7.39
RSC (me l^{-1})	=	Nil

Ground water quality of different farmers field used for irrigation purpose

Fig. 1 The location map of the experimental field representing the groundwater quality used for irrigation purposes

Table 1. Treatments of the best conservation agriculture-based technologies in the rice-wheat system at farmers' fields.

Scenarios	Treatment symbol	Treatment details	Irrigation	Tillage	Residue*
Sc-1	PTR/CTW	Conventional farmer's practice (puddled transplanted rice - conventional tillage wheat)	Surface	Rice: 2 harrow, 2 tiller, 1 laser levelling and puddling with harrow Wheat: 1 harrow, 1 tiller, 1 rotavator	No crop residue retain
Sc-2	PTR+RI/ CTW+RM	PTR with 1/3rd wheat residue incorporation – conventional tillage wheat with rice residue mulch/ anchored	Surface	Rice: 1 harrow, 1 tiller, 1 laser levelling before the start of experiment Wheat: 1 harrow, 1 tiller, 1 rotavator	1/3rd crop residue was incorporated in both rice and wheat crop
Sc-3	SIS-RTDSR+ RI/ZTW-RM	Reduce tillage direct seeded rice with wheat residue incorporation – zero-tillage wheat with rice residue mulch/ anchored under surface irrigation	Surface	Rice: 1 harrow, 1 tiller, 1 laser levelling before start of experiment Wheat: No tillage	DSR with 1/3rd wheat residue incorporation and ZTW with 1/3rd anchored rice residue
Sc-4	SPRL-RTDSR +RI/ ZTW+ RM	Reduce tillage direct-seeded rice with wheat residue incorporation – zero tillage wheat with rice residue mulch/ anchored under sprinkler irrigation	Sprinkler	Rice: 1 harrow, 1 tiller, 1 laser levelling before start of experiment Wheat: No tillage	DSR with 1/3rd wheat residue incorporation and ZTW with 1/3rd anchored rice residue

SIS: Surface irrigation system, SPRL: Sprinkler irrigation system, PTR: Puddled transplanted rice, CTW: Conventional tillage wheat; RTDSR; Reduce tillage direct seeded rice, ZTW: Zero tillage wheat, RI: residue incorporation, RM: Residue mulch.

*One-third residue refers to the actual amount of crop residue left anchored in the field after combine harvesting, while all loose residues are completely removed.

and levelled fields. Wheat was grown during the *rabi* season (November to April) using variety KRL 210 at a seed rate of 100 kg ha^{-1}. Recommended fertilizer doses 80:60 kg N:P ha^{-1} for rice and 150:60 kg N:P ha^{-1} for wheat were applied.

Irrigation was applied according to crop needs and field conditions. In PTR, irrigation was applied almost daily for the first 30–35 days after transplanting, then at weekly intervals. In DSR, irrigation was scheduled every 4–5 days under surface irrigation (when hairline cracks appeared) and on alternate days under sprinkler irrigation. Wheat irrigation was scheduled at critical growth stages to maintain optimal soil moisture throughout its growth period. All crops were harvested at physiological maturity using a combine harvester.

Estimation of crop yield

Crops were manually harvested from randomly selected 3 m × 3 m quadrates at 4 locations within each treatment plot. The harvested samples were air-dried, followed by manual threshing. Subsequently, the entire treatment plots of 1000 m² were harvested using a combine harvester. Grain yield obtained from the 3 m × 3 m quadrates was extrapolated to a hectare basis and expressed in Mg ha^{-1}.

Statistical analysis

To assess the statistical significance of treatment effects across villages, villages effect across the treatments, Analysis of Variance (ANOVA) was conducted based on a randomized complete block design (RCBD) using the GLM procedure in the R software package. A pooled analysis over five years was performed, and treatment means were compared using the critical difference (LSD, p = 0.05).

Results and Discussions

Irrigation water quality and initial soil characteristics

Groundwater used for irrigation at the four farmer sites showed a clear contrast between salinity-dominated and sodicity-dominated hazards (Table 2). Electrical conductivity (EC) ranged from 1.06 dS m^{-1} at Sambhli to 4.29 dS m^{-1} at Kaith. Residual sodium carbonate (RSC) values were negligible at Kaith site but high at Geong site (5.2 me l^{-1}) and moderate at Bahupur site (2.5 me l^{-1}), indicating that some site irrigation water supply producing a sodicity hazard rather than pure salinity. The initial soils were strongly alkaline (pH 8.7–9.6 in the 0–30 cm profile) with low EC (0.186–0.672 dS m^{-1}) Table 3, which is a

Table 2. Groundwater quality used for irrigation purpose at various farmer's field

Cropping sequence	Site	Village	$EC_{1:2}$ (dS m^{-1})	pH	RSC (me l^{-1})
Rice-Wheat	I	Sambhli (Karnal)	1.06	8.13	0.90
	II	Geong (Kaithal)	1.32	8.66	5.2
	III	Bahupur (Panipat)	2.80	8.20	2.50
	IV	Kaith (Panipat)	4.29	7.39	Nil

Where, $EC_{1:2}$ = Electrical conductivity of soil solution (1:2); RSC = Residual sodium carbonate.

Table 3. Initial characteristics of the soil at various farmer's field

Cropping sequence	Site	Village	$pH_{1:2}$		$EC_{1:2}$ (dS m^{-1})	
			0-15	15-30	0-15	15-30
Rice-Wheat	I	Sambhli (Karnal)	8.77	9.06	0.202	0.186
	II	Geong (Kaithal)	9.22	9.61	0.277	0.274
	III	Bahupur (Panipat)	8.79	9.10	0.271	0.225
	IV	Kaith (Panipat)	9.01	9.06	0.669	0.672

Where, $EC_{1:2}$ = Electrical conductivity of soil water suspension (1:2); $pH_{1:2}$ = pH of soil water suspension (1:2).

combination of typical sodic soils, where exchangeable sodium is the main constraint, even though soluble salt concentrations remain moderate.

Such water and soil combinations define a mixed problem domain across sites: some fields are primarily sodic (high RSC, high pH) such as Geong site, others saline (high EC, low RSC). Sodicity reduces infiltration and hydraulic conductivity and restricts root growth (Abrol and Bhumbla, 1979), while salinity imposes osmotic stress and ion toxicity that limit water uptake and nutrient balance (Rengasamy, 2010).

Rice yield under tillage-residue and irrigation systems

Five-year pooled rice grain yields (Table 4) averaged 3.50 Mg ha^{-1} across all sites. The highest pooled mean occurred under SPRL–RTDSR + RI (sprinkler irrigated reduced-tillage direct-seeded rice with residue incorporation), giving 3.71 Mg ha^{-1} (111 % of PTR yield), whereas conventional puddled transplanted rice averaged 3.33 Mg ha^{-1}. The improvement from PTR to RTDSR + sprinkler + residue was statistically significant. The yield gain was site dependent as Bahupur and Geong exhibited larger gains than Kaith, reflecting local interactions between irrigation water quality, soil sodicity, and microclimate. The yield advantage of SPRL–RTDSR + RI arises from interacting effects. Sprinkler irrigation minimizes standing water and puddling, thereby avoiding soil structural degradation and reducing water losses (Humphreys *et al.,* 2010). Reduced tillage and residue incorporation increase surface cover and organic matter input, improving aggregation, infiltration, and microbial activity (Fagodiya *et al.,* 2024a,b). Residue retention also enhances labile C supply and nutrient cycling, which is particularly beneficial under sodic or saline-sodic water regimes (Choudhury *et al.,* 2014). Comparable or superior yields under DSR compared with PTR have been documented widely in South Asia when residue and irrigation are properly managed. DSR can reduce irrigation water use by 25–35% and improve energy efficiency, making it more suitable in areas with poor groundwater quality (Bhatt *et al.,* 2016).

Wheat yield patterns across tillage-residue-irrigation systems

The five-year pooled wheat yields averaged 5.57 Mg ha^{-1} (Table 5). The highest mean (5.89 Mg ha^{-1}) was obtained under sprinkler irrigated ZTW with rice residue mulch (SPRL–ZTW + RM), which was 17.8 % higher than the CTW. Zero-tillage wheat with residue mulch treatments under both surface and sprinkler irrigation (SIS–ZTW + RM and SPRL–ZTW + RM) achieved more than 13 % yield gains relative to CTW. Across sites, zero-till with residue under sprinkler irrigation consistently produced the highest yields. Zero-tillage with residue mulch benefits wheat through multiple mechanisms in salt-affected soils: the residue layer suppresses evaporation and surface salt accumulation, moderates temperature, and supplies organic C that enhances soil aggregation and root proliferation (Jat *et al.*, 2024). Sprinkler irrigation distributes water uniformly, reducing localized ponding and salt concentration. When

Table 4. Rice yield under different tillage residue and irrigation management practices in salt-affected environment at farmers' field (Results are 5-years pooled average)

Villages	Pooled average rice grain yield (Mg ha^{-1})					
	PTR	PTR+RI	SIS-RTDSR+RI	SPRL-RTDSR+RI	Mean	CD (0.05)
Shambhali (Karnal)	3.34	3.28	3.57	3.57	3.44	0.10
Geong (Kaithal)	3.12	3.60	3.43	3.73	3.47	0.15
Bahupur (Panipat)	3.63	3.90	3.33	4.04	3.73	0.12
Kaith (Panipat)	2.97	3.62	3.31	3.49	3.35	0.19
Mean	3.33	3.53	3.41	3.71	3.50	0.08
RGY%	100	106.0	102.40	111.41	-	-

Where, PTR = Puddled transplanted rice, RTDSR = Reduce tillage direct seeded rice; RI = 1/3rd wheat residue incorporation, SIS = Surface irrigation, SPRL = sprinkler irrigation.

Table 5. Wheat yield under different tillage residue and irrigation management practices in salt-affected environment at farmers' field (Results are 5-years pooled average)

Villages	Pooled average wheat grain yield (Mg ha^{-1})					
	CTW	CTW+RI	SIS-ZTW+RM	SPRL-ZTW+RM	Mean	CD (0.05)
Shambhali (Karnal)	5.44	6.02	5.93	6.48	5.97	0.55
Geong (Kaithal)	4.43	5.45	5.48	5.71	5.27	0.45
Bahupur (Panipat)	5.46	6.22	6.16	5.99	5.96	0.50
Kaith (Panipat)	4.68	5.17	5.12	5.39	5.09	0.43
Mean	5.00	5.72	5.67	5.89	5.57	
RGY%	100	114.4	113.4	117.8	111.4	

Where, CTW = Conventional tillage wheat sowing; CTW+RI= Conventional tillage wheat with rice residue incorporation; SIS-ZTW+RM = Zero tillage wheat with rice residue mulch under surface irrigation system; SPRL-ZTW+RM = Zero tillage wheat with rice residue mulch under sprinkler irrigation system

combined with residue mulch, it maintains a more favorable rhizosphere salinity and aeration status (Singh *et al.,* 2020). Numerous studies confirm that CA-based wheat systems improve productivity and water-use efficiency in the IGP, particularly under marginal water-quality conditions (Soni *et al.,* 2021). Over time, ZT + residue systems also increase soil organic carbon and microbial biomass, thereby improving nutrient uptake and resilience against salinity stress (Chandra *et al.,* 2014).

There are several reasons for better performance of crops under tillage and residue management practices. The sodic soils such as at Geong site, suffer clay dispersion, poor aggregation, and reduced infiltration (Abrol and Bhumbla, 1971). The incorporation/retention of residue with reduced/no-tillage practices increases organic matter and microbial polysaccharides, which promote aggregation and hydraulic continuity (Bhattacharyya *et al.,* 2015; Fagodiya *et al.,* 2025). Sites irrigated with high-RSC water, particularly Geong, face sodium hazards. The micro irrigation practice particularly sprinkler irrigation, organic matter addition through crop residue retention can restrict sodium buildup and improve leaching efficiency and mitigating sodicity effects (Minhas and Gupta, 1992; Sharma and Minhas, 2005). Sprinkler irrigation decreases evaporation and limits salt accumulation at the surface, while residue mulch further suppresses evaporative flux, reducing osmotic stress in the root zone (Rhoades *et al.,* 1992). Besides this, the addition of residue retention enhances soil organic carbon and microbial biomass C, improving nutrient availability under salt-affected conditions. These improvements accumulate over multiple years, explaining the steady yield advantages observed under CA + sprinkler treatments.

Practical implications, limitations, and future needs

Where irrigation water has high RSC, chemical amendments (e.g., gypsum) and drainage improvement remain essential for reclamation (Abrol and Bhumbla, 1971). However, where such inputs are limited, CA practices such as residue retention, reduced/zero tillage, and improved irrigation methods can mitigate yield losses and sustain productivity until reclamation progresses. This study reinforces that bundled technologies (residue + CA tillage + efficient irrigation) improve both crop performance and soil quality. Such combinations reduce vulnerability to poor water quality, enhance physical and biological soil health, and contribute to long-term reclamation and land degradation neutrality in salt-affected zones (Mukhopadhyay *et al.,* 2023). The present results from farmer fields capture real-world variability but lack detailed measurements of salinity and sodicity parameters. Future studies should quantify changes in ESP, infiltration rate, and soil microbial carbon to evaluate reclamation trajectories under CA practices in salt-affected soils. Integrating socio-economic assessments will also clarify adoption feasibility under smallholder conditions.

Conclusions

The five-year on-farm evaluation in a salt-affected environment in Haryana demonstrated that CA-based management practices significantly enhance the productivity of the RWS. The combination of reduced tillage direct-seeded rice (RTDSR) and zero tillage wheat with residue retention (ZTW+RM) and sprinkler irrigation achieved the highest system productivity, outperforming the conventional farming practice. The findings highlight the potential of CA-based practices, combined with salt-tolerant varieties (Basmati CSR 30 and KRL 210), as a viable strategy for sustaining productivity and promoting ecological restoration in degraded lands. Incentives for residue retention, custom-hiring centres for CA machinery, and farmer training on water-efficient practices can accelerate adoption across salt-affected agroecosystems.

Acknowledgements

This research was part of the Consortia Research Platform on Conservation Agriculture (CRP on CA) funded by Indian Council of Agricultural Research (ICAR), New Delhi. The authors are grateful to the Prioritization, Monitoring and Evaluation (PME) cell of ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal for internal review and approval of the manuscript (Research article/45/2025).

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Received: December 03, 2025; Accepted: May 20, 2026