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Climate-resilient agriculture for sustainable management of sodic soils in Uttar Pradesh

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Abstract

Sodicity is a major constraint to agricultural productivity in the Indo-Gangetic region, particularly in Uttar Pradesh. The present study assessed the impact of climate-resilient agricultural interventions on land use, soil health, crop productivity and profitability in four sodic-prone districts of Uttar Pradesh, namely Pratapgarh, Bhadohi, Kaushambi and Kanpur Dehat. Data were obtained through Farming System Typology (FST) records. Soil pH and electrical conductivity declined from 10.91 to 9.68 and 2.52 to 0.88 dS m⁻¹, respectively, whereas organic carbon increased from 0.15 to 0.43%. NICRA farmers also recorded higher productivity and net returns for several salt-tolerant crops. In wheat variety KRL-210, productivity and net return were 29.97 q ha⁻¹ and Rs.29,674 ha⁻¹ among NICRA farmers compared with 25.06 q ha⁻¹ and Rs.21,678 ha⁻¹ among non-NICRA farmers. The findings indicate that integrated climate-resilient interventions can improve land utilization, soil health, crop productivity and farm profitability in sodic environments.

Keywords: Sodic soils, climate-resilient agriculture, farming system typology and salt-tolerant

Introduction

Salt-affected soils are among the major forms of land degradation that constrain agricultural productivity, soil health and the sustainable use of land resources. Among the different categories of salt-affected soils, sodic soils are particularly problematic because excessive accumulation of exchangeable sodium adversely affects soil structure and hydraulic properties. Sodicity promotes clay dispersion, surface crusting, poor infiltration, reduced hydraulic conductivity, restricted aeration and impaired root growth, ultimately resulting in poor crop establishment and reduced crop productivity (Basak *et al.*, 2022) ^[1]. In addition, high soil pH and sodium-induced nutrient imbalances can further restrict nutrient availability and plant growth in sodic environments.

The problem of salt-affected soils is particularly important in South Asia, where large areas of agricultural land are located in the Indo-Gangetic Plains. India has approximately 6.73 million ha of salt-affected soils, including a substantial area of sodic soils, much of which occurs in the alluvial plains of northern India (ICAR, 2026) ^[2]. Sodicity and alkalinity are important constraints to agricultural development in the Indo-Gangetic region, requiring appropriate combinations of soil amendments, water management, drainage and salt-tolerant crops for successful reclamation and sustainable utilization (Kumar *et al.*, 2022) ^[3].

Uttar Pradesh has the largest concentration of salt-affected soils in India, with approximately 1.37 million ha affected (ICAR-CSSRI, 2026) ^[4]. The majority of these soils are characterized by high soil pH, elevated exchangeable sodium percentage (ESP) and variable electrical conductivity, making soil sodicity a major constraint to agricultural productivity and rural livelihoods in the state. The occurrence of sodic soils in Uttar Pradesh is closely associated with the alluvial landscapes of the Indo-Gangetic Plain, where poor drainage, waterlogging, groundwater conditions and sodium accumulation can contribute to the development and persistence of soil degradation. These conditions can substantially reduce the productive potential of agricultural land and increase the risk of land abandonment where reclamation and appropriate management practices are not adopted.

The consequences of sodicity extend beyond reductions in crop yield. Deterioration of soil structure reduces water movement and root-zone aeration, while high pH and sodium dominance can cause nutritional disorders and restrict root development. Consequently, sodic soils may exhibit substantial yield gaps compared with non-sodic soils. However, sodicity is not necessarily an irreversible form of land degradation. Appropriate reclamation and management practices, including the application of calcium-bearing amendments such as gypsum, improved drainage and leaching, incorporation of organic materials, and cultivation of sodicity-tolerant crops and varieties, can substantially improve soil conditions and restore agricultural productivity (Stavi *et al.*, 2021; ICAR, 2026) [2, 5].

In Uttar Pradesh, field-level reclamation programmes have demonstrated the potential for restoring severely degraded sodic lands to productive agriculture. ICAR-CSSRI has reported that integrated approaches involving gypsum, organic amendments, green manuring and salt-tolerant crop varieties can reduce yield losses and bring previously uncultivated sodic land back into production (ICAR-CSSRI, 2026) [4]. Such interventions are particularly relevant for small and marginal farmers whose livelihoods depend heavily on the productivity of limited land resources.

Against this background, Uttar Pradesh represents an important region for assessing the extent and implications of salt-affected and sodic soils for agricultural land use and productivity. The distribution and severity of salt-affected soils vary across districts, making district-level assessment important for understanding their effects on crop production and for developing location-specific reclamation and management strategies. Therefore, the present study was undertaken in selected sodic-prone districts of Uttar Pradesh to assess the extent and impact of salt-affected and sodic soils on agricultural land use and crop productivity, with particular emphasis on changes in land utilization, soil health, crop performance and the potential of climate-resilient management practices for the sustainable utilization of affected lands.

Objectives

1. To assess the extent and distribution of salt-affected and sodic soils and their impact on agricultural land use and crop productivity in selected districts of Uttar Pradesh.
2. To evaluate suitable reclamation and climate-resilient management practices for improving soil health, crop productivity and the sustainable utilization of sodic soils.

2. Materials and Methods

2.1 Study Area

The present study was conducted in four selected districts of Uttar Pradesh representing sodicity-affected areas, namely Kanpur Dehat, Bhadohi, Pratapgarh and Kaushambi. These districts were selected based on the prevalence of sodic soils and the implementation of climate-resilient agricultural interventions under the National Innovations in Climate Resilient Agriculture (NICRA) programme. The study focused on farming households located in selected NICRA villages and corresponding non-NICRA areas within the study districts.

The selected districts represent variation in prevailing farming systems and provided a suitable basis for assessing agricultural production under sodicity-prone conditions. The study considered farming households associated with the selected villages to document differences in land use, crop production and management practices under NICRA and non-NICRA conditions. The NICRA framework emphasizes assessment of

local vulnerability, documentation of existing farming systems and implementation of location-specific interventions at the farm and household levels.

2.2 Data source and Farming System Typology

The study was primarily based on secondary and field-level data recorded through the Farming System Typology (FST) in the selected sodicity-affected districts. Under the FST approach, farming households were characterized according to their major agricultural enterprises and resource-use patterns, including crop production and other farm-based activities. This approach facilitated systematic documentation of farming systems at the household level and enabled comparison of agricultural performance across different categories of farmers.

The use of Farming System Typology was consistent with the NICRA framework, under which farming systems are documented and assessed at the farm and household levels to identify existing production systems, vulnerabilities and opportunities for climate-resilient interventions. The FST-based approach also provided a framework for comparing crop productivity, land use and economic performance between NICRA and non-NICRA farming households in the selected study areas.

2.3 Selection and classification of farmers

For the purpose of comparison, farmers were classified into two groups:

1. **NICRA farmers:** farmers associated with villages/farming systems where interventions were implemented under the NICRA programme.
2. **Non-NICRA farmers:** farmers following conventional/existing farming practices in comparable areas but not receiving the selected NICRA interventions.

The comparison was made using crop-wise productivity and economic returns. This approach enabled assessment of differences in agricultural performance between farmers exposed to the NICRA interventions and those following conventional practices.

2.4 Data collection

Information related to crop production was compiled from the available Farming System Typology (FST) records of the selected farmers. The major variables considered in the study included crop and cropping system, cultivated area, crop productivity/yield ($q\ ha^{-1}$), prevailing farm-gate or market price of produce, cost of cultivation, gross return, net return ($Rs.\ ha^{-1}$), and the comparative performance of NICRA and non-NICRA farmers.

Where required, yield observations were standardized and expressed on a per-hectare basis ($q\ ha^{-1}$) to facilitate comparison among farmers with different operational holding sizes.

2.5 Estimation of crop productivity

Crop productivity was expressed in quintals per hectare ($q\ ha^{-1}$). For each crop, productivity was calculated as:

$$\text{Crop productivity} = \frac{\text{Total crop production (q)}}{\text{Area under crop (ha)}}$$

The use of standardized yield per unit area facilitates comparison of production performance across farms and farmer categories. The Government of India's agricultural statistics system similarly reports crop yield and production indicators on an area basis.

2.6 Estimation of cost and returns

The economic performance of the crops was assessed by estimating the **gross return and net return per hectare**. The cost components were considered following the general principles used in the Government of India's Comprehensive Scheme for studying the Cost of Cultivation of Principal Crops. The official cost-of-cultivation framework considers expenditure on labour, machinery, inputs, land-related costs, fixed capital and family labour through established cost concepts.

Gross return was calculated as:-

$$\text{Gross return} = \text{Total Crop Yield (Q)} \times \text{Price of Produce (Rs)}$$

Net return was estimated as:

$$\text{Net Return} = \text{Gross Return} - \text{Total Cost of Cultivation}$$

This method is consistent with the agricultural economics literature and Government of India cost-and-return estimation practices, where net return is derived by deducting the relevant cost of cultivation from gross returns.

2.7 Comparative analysis

The productivity and profitability of NICRA and non-NICRA farmers were compared crop-wise. The following indicators were used to assess the magnitude of difference:

Percentage change

$$\text{Percentage Change} = \frac{\text{Increase}}{\text{Original Value}} \times 100$$

The percentage change was calculated separately for crop productivity and net returns. A positive value indicated a higher value for NICRA farmers relative to non-NICRA farmers, whereas a negative value indicated a lower value.

The comparison of productivity and economic returns was undertaken to assess the association of NICRA interventions with farm-level performance under sodicity-prone farming conditions. NICRA documentation emphasizes the assessment of location-specific interventions and their contribution to resilience and farm-level outcomes.

2.8 Statistical analysis

The collected data were tabulated and analyzed using descriptive statistical techniques, including mean, percentage and percentage difference/change. Mean crop productivity and net returns were calculated separately for NICRA and non-NICRA farmers. The results were presented in tables and figures for facilitating comparison across the four study districts.

Where the number of observations permits, the difference between NICRA and non-NICRA farmers may additionally be tested using an appropriate statistical test such as an independent-samples t-test, with the level of significance reported along with the test statistic. This would provide statistical evidence regarding whether observed differences in productivity and profitability are statistically significant rather than merely descriptive.

3. Results and Discussion

3.1 Natural Resource Management Interventions

3.1.1 Laser land levelling

Laser land levelling was demonstrated in Pratapgarh district on 20.23 ha and was associated with a 28.62% increase in paddy

production. The result indicates that precise field grading can contribute to more uniform water distribution and improved field management. The observed production response is agronomically plausible because precision levelling reduces micro-topographic variation, thereby improving the uniformity of irrigation and crop establishment.

Evidence from the Indo-Gangetic Plains supports the resource-conservation potential of precision levelling. Jat *et al.* (2009) ^[8] found that laser-assisted precision land levelling improved rice-wheat system productivity and reduced irrigation water use, while Devkota *et al.* (2021) ^[9] demonstrated substantial improvements in irrigation water productivity under laser-levelling treatments in eastern India. These findings provide a scientific basis for interpreting the 28.62% production improvement observed in Pratapgarh as potentially linked to improved field uniformity and water-use efficiency, although the district-level observation itself should not be interpreted as a controlled experimental estimate of causality.

The intervention therefore appears particularly relevant where uneven land surfaces cause non-uniform water application. Its value may extend beyond yield improvement because better field uniformity can also facilitate mechanized operations and improve the efficiency of other inputs. The Pratapgarh result consequently supports the inclusion of laser land levelling within broader resource-conservation strategies rather than treating it solely as a land-preparation operation.

3.1.2 Soil amendments

In Kaushambi district, application of sulphur at 20 kg ha⁻¹ to mustard variety RH-725 under rainfed conditions was associated with a 25% increase in production and a 38% increase in net return. The larger proportional improvement in net return than in production suggests that the intervention provided an appreciable economic response in addition to its agronomic effect.

Sulphur is an important secondary nutrient in oilseed crops because it contributes to protein synthesis, enzyme activity and oil formation. Experimental work with Indian mustard has demonstrated positive responses of seed yield, oil content and nutrient uptake to sulphur application (Pachauri & Trivedi, 2014) ^[6]. More recent work in the Bundelkhand region likewise showed that sulphur fertilization improved mustard yield and profitability, particularly when combined with appropriate micronutrient management (Bhinda & Singh, 2023) ^[7]. The response observed in Kaushambi is therefore consistent with the broader evidence that correcting sulphur deficiency can improve mustard performance, especially in soils where nutrient availability is limiting.

Because the present district-level result was obtained under rainfed conditions, the response is also important from a risk-management perspective. Appropriate correction of secondary nutrient deficiency can improve the crop's capacity to utilize available moisture and nutrients. Nevertheless, the reported 25% and 38% improvements should be treated as intervention-level observations because the supplied dataset does not provide replicated treatment and control measurements for a statistical significance test.

3.1.3 Microbial consortium

Halo-MIX, a microbial consortium intended for salt-affected soils, was demonstrated in Pratapgarh. The soil dataset showed a progressive decline in pH and electrical conductivity accompanied by an increase in organic carbon and available nutrients. Soil pH decreased from 10.91 in 2015-16 to 9.68 in

2022-23, while EC declined from 2.52 to 0.88 dS m⁻¹. Organic carbon increased from 0.15 to 0.43% over the same period.

Available N increased from 175.51 to 271.15 kg ha⁻¹, available P from 13.65 to 21.88 kg ha⁻¹ and available K from 143.40 to 216.16 kg ha⁻¹. Available sulphur, zinc, boron and ferrous iron also increased during the observation period. These changes collectively indicate an improvement in the measured chemical fertility status of the monitored soil (Table 1.).

The trend is compatible with the intended function of Halo-MIX. ICAR-CSSRI describes Halo-MIX as a consortium of halophilic plant-growth-promoting and nutrient-mobilizing microorganisms developed for salt-affected soils. Earlier CSSRI observations also documented reductions in soil pH and

exchangeable sodium together with increases in organic carbon, available N and P and microbial indicators following inoculation with halophilic microbial consortia (ICAR-CSSRI, 2018). Thus, the improvement observed in Pratapgarrh is biologically consistent with the mechanism of the technology.

However, the dataset represents observations across different years and does not include a contemporaneous untreated control. Consequently, the temporal changes should be described as improvements associated with the intervention and associated soil-management programme rather than as statistically proven effects caused exclusively by Halo-MIX. This qualification is important when interpreting district-level demonstrations in a research manuscript.

Table 1: Temporal changes in selected soil chemical properties following microbial consortium-based soil management in Pratapgarrh.

Year	pH	EC (dS m ⁻¹)	OC (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
2015-16	10.91	2.52	0.15	175.51	13.65	143.40
2019-20	10.43	1.38	0.22	223.33	18.27	155.16
2022-23	9.68	0.88	0.43	271.15	21.88	216.16

Note: EC = electrical conductivity; OC = organic carbon. Values are from the district-level dataset supplied by the authors.

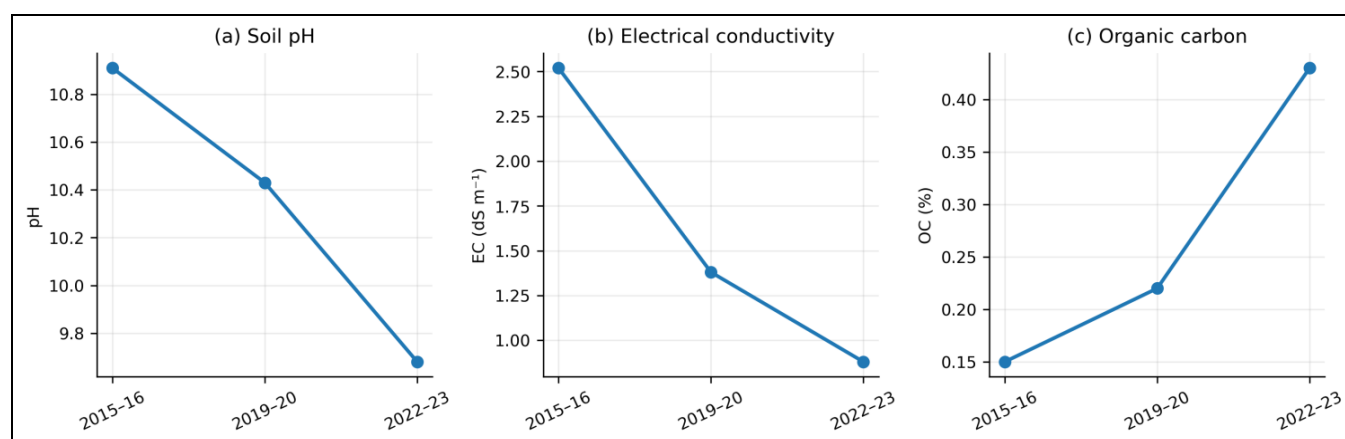


Fig 1: Temporal changes in soil pH, electrical conductivity and organic carbon in Pratapgarrh following adoption of microbial consortium-based soil management.

The graphical trend further illustrates the direction of change: pH and EC moved downward across the monitoring period, whereas organic carbon increased. Numerically, pH declined by approximately 11.3% and EC by 65.1%, while organic carbon increased by approximately 186.7% between 2015-16 and 2022-23. The simultaneous movement of these indicators is important because excessive alkalinity and salinity can restrict nutrient availability and root activity, whereas greater organic carbon can support biological activity and nutrient cycling. The figure therefore provides a concise visual representation of the soil-quality changes shown in Table 1.

3.1.4 Green manuring

Green manuring was adopted over 95 ha in Pratapgarrh, principally before paddy establishment. The district records indicate a saving equivalent to approximately 300-400 kg of *Sesbania* seed/biomass, valued at about ₹1,240. The principal agronomic significance of the practice is the recycling of biomass and biologically fixed nitrogen into the soil before establishment of the succeeding rice crop.

Green-manure research in the rice-wheat system has demonstrated improvements in soil organic matter and total nitrogen under *Sesbania*-based treatments compared with fallow

management. Earlier work with *Sesbania rostrata* also showed that incorporation of green manure could contribute substantial biologically fixed nitrogen and increase rice yield. These findings support the interpretation that green manuring can function as both a nutrient-supplying practice and a soil-quality intervention. (Mandal *et al.*, 2003) ^[10]

The 95-ha coverage in Pratapgarrh is therefore important from an adoption perspective. Rather than representing only a small experimental plot, the practice was implemented over a comparatively large area. Its potential contribution to reducing dependence on externally supplied nutrients, recycling biomass and improving soil organic matter makes it particularly relevant to sustainable rice-based systems.

3.2 Crop Enterprise Interventions

3.2.1 Salt-tolerant varieties

The crop-enterprise demonstrations showed higher productivity and net returns for the salt-tolerant varieties under NICRA farmer conditions than under the corresponding non-NICRA farmer conditions. The magnitude of improvement differed among crops and varieties. CSR-36 rice showed the largest proportional productivity increase, whereas RH-749 mustard showed the smallest difference among the four comparisons.

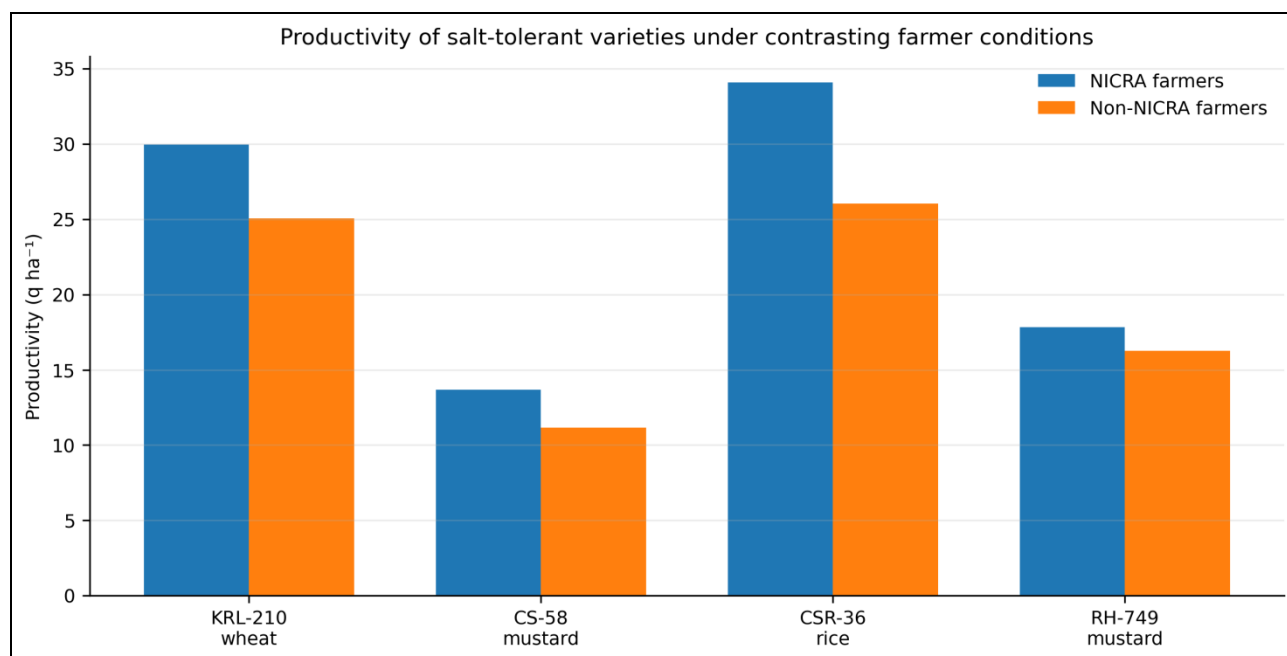
Table 2: Productivity and net return of salt-tolerant varieties under NICRA and non-NICRA farmer conditions.

District	Crop/variety	NICRA productivity (q ha ⁻¹)	Non-NICRA productivity (q ha ⁻¹)	Change (%)	NICRA net return (Rs. ha ⁻¹)	Non-NICRA net return (Rs. ha ⁻¹)	Change (%)
Pratapgarh	Wheat (KRL-210)	29.97	25.06	19.59	29,674.44	21,677.78	36.89
Pratapgarh	Mustard (CS-58)	13.67	11.17	22.38	53,367.78	42,082.78	26.82
Pratapgarh	Rice (CSR-36)	34.10	26.03	31.00	37,900.00	24,133.33	57.04
Bhadoli	Mustard (RH-749)	17.83	16.25	9.72	53,875.00	51,337.00	4.94

Note: Change (%) = [(NICRA – non-NICRA)/non-NICRA] × 100. Values are calculated from the supplied district-level data.

Productivity increased by 19.59% for KRL-210 wheat, 22.38% for CS-58 mustard, 31.00% for CSR-36 rice and 9.72% for RH-749 mustard (Table 2). The corresponding changes in net return were 36.89, 26.82, 57.04 and 4.94%, respectively. Thus, the

economic response was not always proportional to the yield response, indicating that the profitability of a technology depends on both production and the associated economics of cultivation.

**Fig 2:** Comparative productivity of salt-tolerant crop varieties under NICRA and non-NICRA farmer conditions.

The productivity comparison in Figure 2 shows that all four demonstrated varieties had higher recorded productivity under NICRA farmer conditions. The largest absolute difference occurred in CSR-36 rice, where productivity increased from 26.03 to 34.10 q ha⁻¹, an increase of 8.07 q ha⁻¹. KRL-210 wheat and CS-58 mustard also showed clear advantages, while the difference for RH-749 was comparatively smaller.

The results are consistent with the established role of salt-tolerant germplasm in maintaining productivity under saline and sodic conditions. ICAR-CSSRI has developed and released salt-tolerant rice varieties including CSR-36, salt-tolerant wheat varieties including KRL-210, and mustard varieties including CS-58. CSSRI also emphasizes varietal adaptation as an economically viable component of salt-affected land management because varietal tolerance can reduce the need to depend solely on expensive soil reclamation measures (ICAR-CSSRI, 2024) ^[11].

The higher productivity recorded in the NICRA demonstrations should nevertheless be interpreted as an outcome of the demonstration package and associated management conditions rather than as evidence that variety alone caused the entire difference. Differences in farmer management, soil condition, input use and local environment can also contribute to the observed contrast.

3.2.2 Economic performance of salt-tolerant varieties

The economic comparison provides an additional measure of the performance of the demonstrations. Among the four varieties, RH-749 mustard recorded the highest absolute NICRA net return (₹53,875 ha⁻¹), followed closely by CS-58 mustard (₹53,367.78 ha⁻¹). However, CSR-36 rice showed the largest proportional improvement over its non-NICRA comparison, with net return increasing by 57.04%.

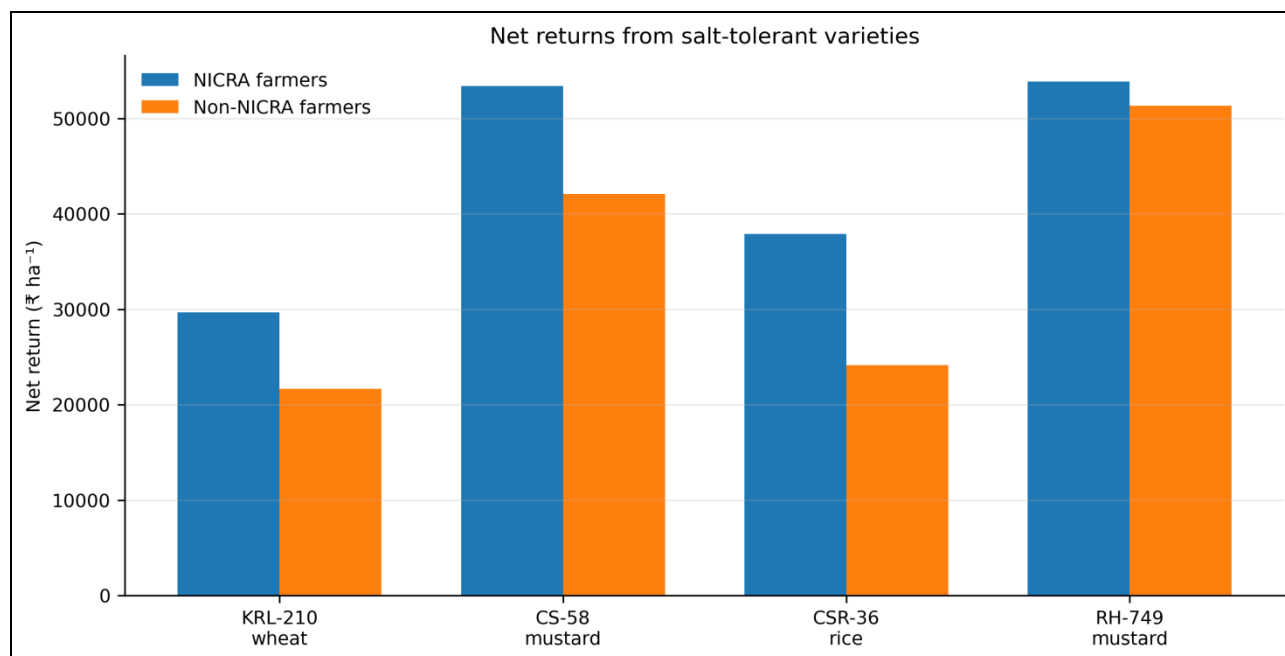


Fig 3: Comparison of net returns from salt-tolerant crop varieties under NICRA and non-NICRA farmer conditions.

Figure 3 indicates that the economic advantage was evident across all four comparisons, although its magnitude varied considerably. The difference was especially pronounced for CSR-36, for which net return increased from ₹24,133.33 to ₹37,900 ha⁻¹. The economic performance of KRL-210 and CS-58 was also clearly higher under the NICRA condition, whereas RH-749 showed a relatively small difference in net return despite its higher absolute value.

These results emphasize that evaluation of stress-tolerant technologies should include profitability in addition to physical yield. ICAR-CSSRI's economic assessment of salt-tolerant mustard varieties similarly indicates that improved varieties can generate substantial economic benefits through their use in salt-affected areas (ICAR-CSSRI, 2024) ^[11]. The present district-level findings therefore support the economic relevance of matching crop varieties with the constraints of the production environment.

3.2.3 Biofortified crops

Biofortified pearl millet AHB-299 was demonstrated in Kaushambi and was associated with a 21% increase in production and a 27% increase in net return. The intervention has importance beyond yield because biofortified pearl millet is intended to improve the nutritional value of the harvested grain. ICAR identifies HHB-299 as a biofortified pearl millet hybrid containing approximately 73 ppm iron and 41 ppm zinc, with a reported grain yield of 32.7 q ha⁻¹ under its recommended production environments (ICAR, 2017) ^[13]. Independent nutritional profiling has also documented the nutritional and phytochemical characteristics of HHB-299 and other biofortified pearl millet materials (Kumar *et al.*, 2023) ^[12]. The Kaushambi result therefore illustrates how crop demonstrations can simultaneously address production and nutritional objectives. The reported 27% improvement in net return further indicates that nutritional enhancement was accompanied by an economic benefit under the local demonstration conditions. Such interventions can be particularly valuable where pearl millet contributes significantly to household food systems, because improved grain nutrient density can provide benefits without requiring a separate food production activity.

3.2.4 Salt-resistant crop cultivation

Salt-resistant crop cultivation was also used as an adaptation strategy. In Kaushambi, beetroot variety Ragini produced 225.67 q ha⁻¹ with a net return of ₹3,27,810 ha⁻¹. In Bhadohi, Bajra NSC-1071P was associated with an 18% increase in production and a 15% increase in net return.

The results demonstrate the practical value of matching crop or genotype with the prevailing soil environment. In salt-affected areas, a tolerant crop can maintain establishment and productivity where a sensitive cultivar may suffer substantial yield losses. The approach complements soil-reclamation measures and is consistent with the long-standing breeding programme of ICAR-CSSRI, which has developed salt-tolerant cultivars for rice, wheat, mustard and other crops (ICAR-CSSRI, 2026) ^[4].

The Kaushambi and Bhadohi results should therefore be interpreted as examples of genotype- and crop-based adaptation. Their usefulness is greatest when integrated with appropriate nutrient, water and soil-management practices rather than considered as a substitute for all other forms of soil improvement.

3.2.5 Short-duration varieties

Short-duration varieties were demonstrated to reduce the crop cycle and improve flexibility within the cropping sequence. In Bhadohi, rice variety Co-51 recorded 52.95 q ha⁻¹ and a net return of ₹1,23,429 ha⁻¹ with maturity reported at approximately 105-110 days under direct-seeded rice management. In Kanpur Dehat, short-duration gram variety RVG-202 produced 21.50 q ha⁻¹ and generated a net return of ₹86,500 ha⁻¹; the variety was also described in the supplied records as resistant to wilt.

The 105-110-day duration reported for Co-51 is consistent with published varietal information. Robin *et al.* (2019) ^[14] described CO 51 as an early-duration rice variety with a 105-110-day maturity period, high yield potential and useful pest and disease resistance. Short-duration cultivars can be valuable in production systems where timely establishment of the succeeding crop is important, because a shorter crop cycle can reduce exposure to late-season climatic risks and increase flexibility in crop scheduling.

The observed productivity and profitability of Co-51 and RVG-202 therefore suggest that short-duration cultivars can contribute to cropping-system resilience. Their benefit is not limited to the yield of the individual crop; the shortened duration can also create opportunities for timely sowing of the succeeding crop and more efficient use of the available growing period.

3.3 Overall performance of the documented interventions

The interventions documented across the districts addressed several interconnected constraints: water distribution, nutrient limitation, soil salinity and alkalinity, soil biological activity, crop nutritional quality and crop-duration constraints. The major outcomes are summarized in Table 3.

Table 3: Summary of major agricultural interventions and observed outcomes.

Intervention	District	Technology/variety	Area/indicator	Major observed outcome
Laser land levelling	Pratapgarh	Laser-guided levelling	20.23 ha	Paddy production +28.62%
Soil amendment	Kaushambi	Sulphur @ 20 kg ha ⁻¹ in RH-725 mustard	Rainfed condition	Production +25%; net return +38%
Microbial consortium	Pratapgarh	Halo-MIX	Salt-affected soil	pH and EC declined; OC and available nutrients increased
Green manuring	Pratapgarh	Sesbania	95 ha	300-400 kg seed/biomass equivalent saving; ₹1,240 value reported
Salt-tolerant wheat	Pratapgarh	KRL-210	Crop enterprise	Productivity +19.59%; net return +36.89%
Salt-tolerant mustard	Pratapgarh	CS-58	Crop enterprise	Productivity +22.38%; net return +26.82%
Salt-tolerant rice	Pratapgarh	CSR-36	Crop enterprise	Productivity +31.00%; net return +57.04%
Salt-tolerant mustard	Bhadohi	RH-749	Crop enterprise	Productivity +9.72%; net return +4.94%
Biofortified crop	Kaushambi	Pearl millet AHB-299	Crop enterprise	Production +21%; net return +27%
Salt-resistant crop	Kaushambi	Beetroot Ragini	Crop enterprise	Productivity 225.67 q ha ⁻¹ ; net return ₹3,27,810 ha ⁻¹
Salt-resistant crop	Bhadohi	Bajra NSC-1071P	Crop enterprise	Production +18%; net return +15%
Short-duration rice	Bhadohi	Co-51	105-110 days	Productivity 52.95 q ha ⁻¹ ; net return ₹1,23,429 ha ⁻¹
Short-duration gram	Kanpur Dehat	RVG-202	Short-duration variety	Productivity 21.50 q ha ⁻¹ ; net return ₹86,500 ha ⁻¹

Note: Outcomes are based on the district-level data supplied by the authors; percentage changes are calculated where paired comparison data were available.

Taken together, the findings indicate that the interventions worked through different but complementary pathways. Laser land levelling targeted water distribution and field uniformity, sulphur application addressed a secondary nutrient constraint, Halo-MIX and green manuring focused on soil fertility and biological processes, and improved crop varieties addressed salinity, nutritional quality and crop-duration constraints. This combination is consistent with the broader principle that sustainable intensification in stress-prone areas requires coordinated management of soil, water and crop resources rather than dependence on a single technology.

The magnitude of response varied among locations and interventions. For example, CSR-36 showed a 31.00% productivity advantage and a 57.04% increase in net return, whereas RH-749 showed comparatively smaller differences. Such variation is expected because technology performance is influenced by baseline soil condition, crop, climatic environment, management intensity and farmer practices. Consequently, the results should be interpreted as evidence of the practical potential of the interventions under the documented district conditions rather than as universal effect sizes.

Overall, the district-level evidence supports the value of location-specific technological packages for improving agricultural productivity, profitability and resilience. The combination of precision land management, improved soil fertility practices, biological interventions and stress-adapted cultivars provides a coherent framework for addressing production constraints in resource-limited and salt-affected farming environments.

Conclusion

The study demonstrated that integrated climate-resilient interventions can improve the productive utilization and management of sodic soils in Uttar Pradesh. Improvements in land use, soil properties, crop productivity and farm returns were observed following the adoption of soil- and water-management practices, green manuring, microbial interventions and stress-

tolerant crop varieties. NICRA farmers generally recorded higher productivity and net returns for the evaluated salt-tolerant crops than non-NICRA farmers. Overall, location-specific integration of resource-conservation practices, soil-health management and suitable crop varieties provides a practical approach for improving productivity and sustainability in sodic agro-ecosystems.

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