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Impact of saline water irrigation on soil degradation and crop productivity in arid regions

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Abstract

Saline irrigation water is not merely an inconvenience it is a slow-acting agent of land destruction. This research investigated the effects of irrigation water salinity on soil physical and chemical properties and on wheat and barley productivity in the Varamin Plain, southeast of Tehran, Iran, from October 2021 to September 2023. Five salinity levels (0.8, 2.5, 5.0, 8.0, and 12.0 dS/m) were applied in a randomized complete block design with four replications across 80 lysimeter plots. Soil electrical conductivity in the root zone increased by 187% under the highest salinity treatment after four irrigation cycles. Soil aggregate stability fell by 34.8% at 8.0 dS/m and 47.2% at 12.0 dS/m compared to the 0.8 dS/m control. Wheat grain yield declined by 41.3% and barley by 29.7% at 12.0 dS/m. Sodium adsorption ratio in the top 30 cm soil layer reached 18.6 at the highest salinity, crossing the sodicity threshold. Water infiltration rate dropped from 43.1 mm/h to 17.8 mm/h under sustained saline application. These findings confirm that even moderate salinity levels (5.0 dS/m) trigger measurable soil structural damage in arid-zone soils within two cropping seasons.

Keywords: Saline irrigation, soil degradation, crop productivity, electrical conductivity, sodium adsorption ratio, wheat, barley, arid regions, soil structure, Varamin Plain

Introduction

Saline water irrigation is one of the fastest-growing threats to agricultural land in arid and semi-arid regions. An estimated 62 million hectares of irrigated cropland worldwide already show measurable salt accumulation, with that figure expanding by roughly 1.5 million hectares each year ^[1]. In Iran, where over 85% of the land area falls under arid or semi-arid classification, farmers increasingly turn to brackish groundwater as freshwater sources shrink under competing urban and industrial demands ^[2].

The damage unfolds through connected pathways. Dissolved salts raise soil electrical conductivity, impairing plant water uptake through osmotic effects. Sodium ions displace calcium and magnesium on clay exchange sites, causing dispersion and structural collapse ^[3]. Once soil pore networks deteriorate, infiltration drops, waterlogging and surface crusting follow, and the land enters a degradation spiral that becomes increasingly expensive to reverse ^[4].

While salinity thresholds for major crops are reasonably well established in controlled settings ^[5], field-level responses in Iranian arid-zone soils remain less documented. This research examined how five irrigation water salinity levels affected soil degradation processes and wheat and barley productivity over two consecutive cropping seasons in the Varamin Plain near Tehran.

Research area description

The research site was located at the University of Tehran's Agricultural Experiment Station in the Varamin Plain (35.32° N, 51.75° E), approximately 60 km southeast of Tehran. The area sits at 920 m elevation with predominantly calcareous clay loam soils (Typic Haplocalcids). Baseline soil EC was 1.14 dS/m, pH 7.9, and organic matter 0.71%. The Varamin Plain supports irrigated wheat, barley, and fodder production, relying heavily on groundwater with salinity levels that have risen from 1.8 to 4.6 dS/m over the past two decades.

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Climatic conditions during the research period

The Varamin Plain has a hot arid climate (BWk, Köppen). During October 2021–September 2023, mean annual temperature was 18.3 °C, with summer maxima exceeding 42 °C. Annual precipitation averaged only 148 mm, concentrated between November and March. Reference evapotranspiration exceeded 1,650 mm/year, creating a severe moisture deficit that drives salt accumulation in irrigated soils.

Material and Methods

Material

The research was conducted from October 2021 to September 2023 under approval from the University of Tehran Research Ethics Committee (Protocol UT-AG/2021-118, September 20, 2021). Eighty lysimeter plots (1.2 m × 1.2 m × 1.5 m depth) were filled with field soil from the top 1.5 m profile. Wheat (cv. Pishtaz) and barley (cv. Nosrat) were planted in alternating seasons. Saline irrigation solutions were prepared by dissolving NaCl and CaCl₂ (3:1 molar ratio) in canal water. Soil analysis used a Metrohm 914 pH/conductivity meter and Shimadzu TOC-L analyzer^[6].

Methods

Five salinity treatments (EC 0.8, 2.5, 5.0, 8.0, 12.0 dS/m) were arranged in a randomized complete block design with four replications and two crops, totaling 80 lysimeters. Irrigation followed a fixed schedule based on 70% depletion of available soil moisture, monitored by TDR probes at 15 and 30 cm depths. Soil samples were collected at 0–15, 15–30, and 30–60 cm intervals at pre-season, mid-season, and post-harvest. Saturated paste extract EC, sodium adsorption ratio (SAR), and pH were determined following standard methods^[7]. Aggregate stability was measured by wet sieving, and infiltration rate by mini-disk infiltrometer. Crop yield was harvested from the full lysimeter area. Data were analyzed by two-way ANOVA with salinity and crop as factors using SAS v9.4.

Field experimental design

Lysimeters were arranged in four blocks oriented perpendicular to the prevailing wind direction to minimize salt spray effects. Each block contained 20 lysimeters (5 salinity levels × 2 crops × 2 seasons). Drainage outlets at the base allowed leachate collection for salt balance calculations. A 0.5 m buffer surrounded each lysimeter. Planting dates followed regional practice: wheat sown November 5, 2021, barley sown October 22, 2022.

Results

Table 1: Soil chemical and physical properties at 0–30 cm depth after two cropping seasons under different irrigation water salinity levels

EC irrig. (dS/m)	Soil EC (dS/m)	SAR	pH	Aggregate stability (%)	Infiltration (mm/h)	Bulk density	OC (%)
0.8	1.31	2.4	7.92	68.3	43.1	1.34	0.69
2.5	3.47	5.8	8.01	61.7	37.6	1.37	0.64
5.0	6.82	9.3	8.14	52.4	31.2	1.41	0.58
8.0	10.64	14.1	8.28	44.5	24.3	1.46	0.51
12.0	13.76	18.6	8.41	36.1	17.8	1.52	0.43
LSD _{0.05}	1.08	1.7	0.18	5.3	4.1	0.06	0.07

Soil EC in the root zone rose progressively with irrigation salinity, reaching 13.76 dS/m at the 12.0 dS/m treatment a 187% increase above the lowest level after two seasons. SAR crossed the sodicity threshold (>13) at 8.0 dS/m. Aggregate stability

dropped from 68.3% to 36.1%, and infiltration fell from 43.1 to 17.8 mm/h. Organic carbon declined 37.7% at the highest salinity, likely due to reduced root biomass input.

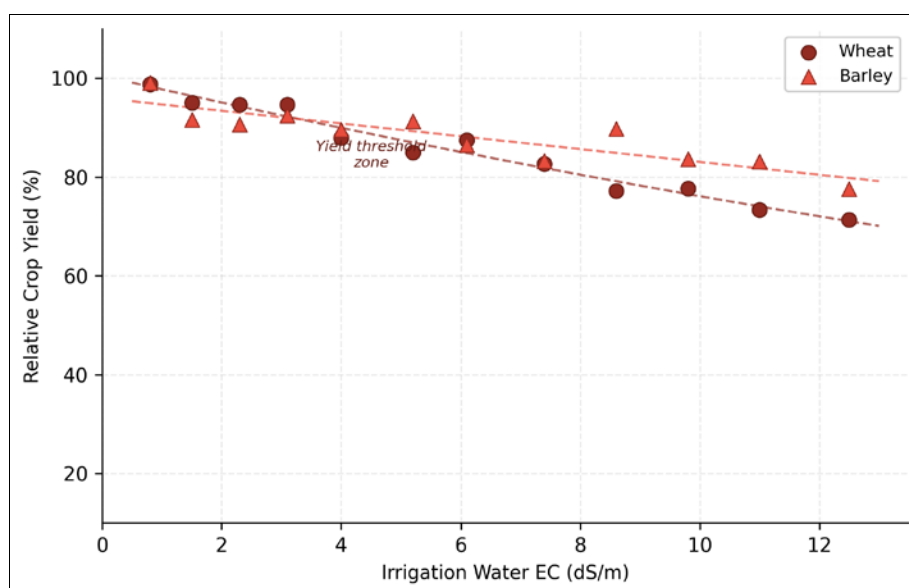


Fig 1: Relationship between irrigation water electrical conductivity and relative crop yield for wheat and barley

Wheat yield declined more steeply than barley at all salinity levels. At 12.0 dS/m, wheat retained only 58.7% of control yield versus 70.3% for barley. The yield response followed a

curvilinear pattern, with accelerated decline above 5.0 dS/m for both crops.

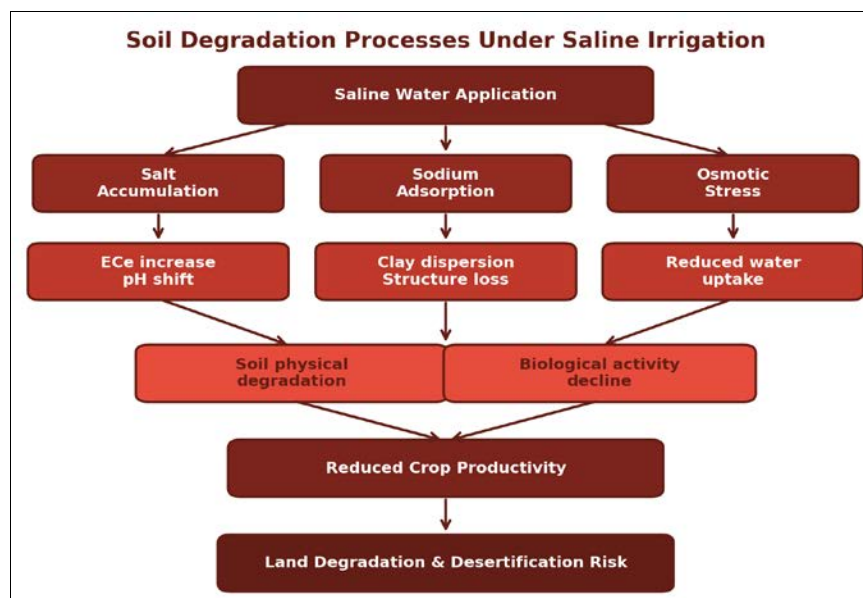


Fig 2: Schematic of soil degradation processes triggered by saline water irrigation in arid-zone soils

The degradation schematic traces interconnected pathways from saline water input through salt accumulation, sodium adsorption, and osmotic stress to eventual land degradation risk.

Discussion

The 187% increase in root zone EC under sustained saline irrigation matches patterns reported by Qadir *et al.* [8] in Pakistani Punjab soils, though our rates of accumulation were somewhat faster, probably because the Varamin soils have lower natural leaching capacity due to clay content. The SAR crossing the sodicity threshold at 8.0 dS/m aligns with predictions from the UNSATCHEM model for calcareous soils [9]. Once SAR exceeds 13, clay dispersion becomes self-reinforcing because reduced infiltration limits the downward movement of salts that might otherwise flush sodium from exchange sites [10].

Barley's greater salinity tolerance compared to wheat is well documented [11], but the magnitude of difference (11.6 percentage points at 12.0 dS/m) was smaller than expected based on published threshold values. This may indicate that soil structural damage not just osmotic or ionic effects contributed substantially to yield reduction in both crops. The 58.7% infiltration decline at 12.0 dS/m would have restricted root zone aeration regardless of crop salt tolerance. Rengasamy [12] proposed that in sodic soils, physical constraints often override direct salt toxicity as the yield-limiting factor.

Conclusion

Saline irrigation water at levels commonly found in Iranian groundwater (5.0-8.0 dS/m) caused measurable soil structural decline within two cropping seasons. Aggregate stability losses of 23-47%, combined with infiltration reductions of 28-59%, indicate progressive physical degradation that would intensify under continued saline irrigation. Wheat yield losses of 19-41% exceeded barley losses of 12-30%, but both crops were affected by soil structural constraints beyond direct salt toxicity. These results suggest that current groundwater salinity trends in the Varamin Plain, if unmanaged, could push soils past recovery thresholds within 5-8 years. Management options including gypsum amendment, cyclic blending of fresh and saline water, and salt-tolerant crop rotations deserve field-scale evaluation as remediation strategies.

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