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Combining chemical and organic treatments enhances remediation performance and soil health in saline-sodic soils

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We investigated the individual and synergistic impact of gypsum, elemental sulfur, vermicompost, biochar, and microbial inoculation on soil health improvement in degrading calcareous saline-sodic soils. We developed Linear and nonlinear soil health quantification frameworks to assess the efficacy of remedial practices. The combined inoculated chemical and organic treatments; gypsum + vermicompost and elemental sulfur + vermicompost with 134% (0.29 versus 0.68) and 116% (0.29 versus 0.62) increases in nonlinear index, significantly increased the efficacy of amendments compared with control. An increase in the overall soil health index ranged between 12 to 134%. Microbial inoculation further enhanced the impact of treatments on soil health. Soil health properties included in the indexes explained 29 to 87% of the variance in wheat growth. The findings bring insight into the cost-effective and environmentally sustainable practices to recover degraded saline-sodic soils. Furthermore, the introduced soil health indexes offer a quantitative evaluation of soil remediation strategies.

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Projections for the future of global population growth suggest that restoration of degraded land is essential to meet the food, feed, and fiber demand of an anticipated 9.8 billion individuals by 2050[1]. Given the rapidly increasing global population, there is an urgent imperative to enhance soil ecosystem services and agricultural production by restoring degraded land resources (FAO, 2018). Soil salinization and sodification are major soil degradation processes that threaten agricultural production and food security primarily in arid and semi-arid regions of the world. The extent of salt-affected soils worldwide is estimated to surpass 833 million ha across over 100 countries, corresponding to 8.7% of the terrestrial land surface[2,3]. Soil salinization leads to the loss of 1.5 million ha of agricultural land and declines the productivity of 46 million ha worldwide each year[4]. Salt input and dissolution of the precipitated salts from irrigation water is the primary driver of soil salinity and alkalinity in arid and semi-arid farmlands, where additional water supply is inevitable to meet high evaporative demand. Rapid population growth and climate change may lead to the expansion of the current irrigated lands from ~ 310 million ha to 1.8 billion ha by 2050, further compounding the salinity challenges[5]. Saline–sodic soil is recognized as a predominant class of salt-affected soils characterized by both high salinity [electrical conductivity (EC) > 4 dS m^{-1}] and sodicity [exchangeable sodium percentage (ESP) > 15% and sodium adsorption ratio (SAR) > 13][6]. Saline-sodic soils have low productivity because of the detrimental impact of excessive salt levels on soil physical, chemical, and biological health and plant growth[7,8]. Excessive exchangeable sodium in saline-sodic soils results in soil structural collapse by dispersing aggregates, solidifying soil, narrowing down the pore size distribution range, and thus obstructing proper nutrient, water, and air cycling[6,9]. Saline and sodic conditions are known to cause typical biochemical and fertility problems, including nutrient deficiencies such as P, Fe, Mn, Zn, and Cu, as well as specific ionic toxicities including Na^+, Cl^-, $H_3BO_4^-$, and HCO_3^-. These conditions also induce osmotic stress on microorganisms and plant cells[10,11]. The cumulative effect of biochemical and physical stresses may ultimately lead to crop failure, economic losses, and irreversible soil degradation depending on the ambient soil salinity and sodicity levels[11,12]. Global annual losses of agricultural production on irrigated lands due to soil salinization are estimated at about $27.3 billion[4] even without including the cost of land remediation in this estimate.

A significant proportion of soils affected by salinity is in arid and semi-arid regions of West Asia and North Africa. The increasing drought in these regions has led to greater reliance on irrigation for farming. However, excessive salinity has resulted in a loss of agricultural land each year. Surface irrigation is the predominant method used in most countries in the region, as smallholder farmers, who make up a significant portion of the agricultural workforce, cannot afford modern irrigation and water treatment technologies[13]. Soil salinity and sodicity pose a significant agricultural and environmental challenge in Iran, where approximately 90% of the country is characterized by arid and semi-arid climatic conditions. Recent estimates suggest that 25.5 and 8.5 million ha of land have slightly moderately and highly saline-sodic soils, respectively, which account for almost 15% and 5.2% of the total land area in the country[14]. Adoption of innovative remediation practices is required to improve the soil health and productivity of the agroecosystems in this region. Organic amendments can bind cations and anions and remove them from the soil solution[8,10]. However, the synergistic effect of multiple organic amendments or combining organic with chemical amendments is largely unclear.

The primary focus of remediation for saline-sodic soils has been on decreasing salt input through the pre-treatment of water and the implementation of precision irrigation practices. In addition, a diverse array of physical practices, such as ploughing, subsoiling, and drainage systems, along with chemical applications, including gypsum, sulfuric acid, basic polyacrylamide, sulfur, iron sulfate, iron disulfide, and organic amendments, such as farm manure, poultry manure, compost, and biochar, have been utilized to mitigate the saline-sodic soils[15–18]. Whilst tillage operations primarily aim to restructure soil particles, chemical remediation methods are focused on replacing exchangeable salts with calcium or hydrogen ions by the addition of gypsum or the dissolution of existing calcium carbonate using acidic agents such as elemental sulfur or sulfuric acid[19]. In contrast, organic remediation of saline-sodic soils entails more comprehensive improvements to the physical, chemical, and biological properties of the soil. Saline-sodic soils often suffer from poor structural quality and exhibit a limited range of pore size classes, each of which supports different soil functions and services[19,20]. Consequently, restrictions in soil aeration, hydraulic conductivity, surface infiltrability, microbial population and diversity, and root penetrability are closely related to the poor soil structure observed in saline-sodic soils. Organic matter serves as a flocculating agent for soil particles that have disintegrated due to the displacement of sodium ions in the exchange sites[21]. Aside from their direct participation in the retention and exchange of vital cations such as Ca^{2+}, K^+, and Mg^{2+}, organic amendments also facilitate the removal of excess salts from the upper soil profile by enhancing water flux and diffusion[22]. Therefore, disparate processes are observed in the remediation of saline-sodic soils by organic and inorganic agents that necessitate comprehension across various organic sources. Although a limited number of investigations attest to the remarkable economic and functional benefits of integrated organic-inorganic remediation strategies, few studies have explored the potential soil health implications of these combined approaches[15,23–25]. Furthermore, there is a notable absence of all-encompassing frameworks for evaluating soil health in saline-sodic soils to measure the rate of improvement resulting from amendment practices. To the best of our understanding, the current study constitutes the inaugural attempt to develop a physical, biological, and chemical soil health assessment framework under combined organic-inorganic saline-sodic soil remediation practices.

Therefore, the objectives of this study were to: (a) develop and assess the synergistic impact of combined remediation practices on the physical, chemical, and biological health of saline–sodic soils, (b) identify the key soil traits that influence the soil health in saline-sodic soils, and (c) develop integrated linear and nonlinear soil health indexes for a comprehensive assessment of amendments. The findings revealed that all amendments significantly improved the physical, chemical, nutritional, and biological health indicators of the studied soil. The combined treatments, particularly GP/ES + VC, were found to be the most effective in promoting soil health, followed by VC. These results suggest that the presence of VC can significantly enhance the impact of GP and ES on improving the health of saline-sodic soils. The numerical value of the SHI increased by 12% to 134% after incorporating amendments into the control soil, depending on the treatments and modeling approach. This demonstrates the positive synergistic effect of multiple amendments on the SHI, particularly those generated by nonlinear modeling. While both linear and nonlinear SHI models showed significant improvement in soil health under all treatments, those with microbial inoculation resulted in higher SHI values. The SHIs were found to be significantly associated with wheat growth indicators, including wet and dry weight, root length, and volume. However, the nonlinear SHI model more accurately predicted wheat growth and productivity parameters than the linear SHI model. Overall,

Table 1 The baseline properties of the study soil and the chemical properties of biochar and vermicompost.

Soil					
Clay (%)	Silt (%)	Sand (%)	Texture	pH	EC (dSm^{-1})
20	20	60	Loam	9.2	10.4
OM (%)	CEC (cmol kg^{-1})	CCE (%)	SAR	ESP (%)	TN (%)
0.62	11.2	22.7	18.1	20.2	0.036
AP (mg kg^{-1})	AK(mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})
5.7	154.8	2.2	2.6	0.16	0.36
Biochar					
pH	EC (dSm^{-1})	OC (%)	N (%)	P (%)	
8.2	0.79	65	0.68	0.28	
K (%)	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	
0.41	330.1	330.1	38.7	62.1	
Vermicompost					
pH	EC (dS m^{-1})	OC (%)	N (%)	P (%)	
7.9	1.6	25	2.03	0.56	
K (%)	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	
0.40	897.4	537	48	170	

EC electrical conductivity, *OM* organic matter, *CEC* cation exchange capacity, *CCE* calcium carbonate equivalent, *SAR* sodium adsorption ratio, *ESP* exchangeable sodium percentage, *TN* total N, *AP* available P, *AK* available K.

the results suggest that organic amendments such as vermicompost have significant potential in improving the health of degraded saline-sodic soils. Organic amendments can also increase the effectiveness of conventional chemical treatments such as gypsum or elemental sulfur in mitigating the adverse impacts of soil salinity and sodicity on plant growth and farm productivity. Given the increasing reliance of intensive farming systems on chemical inputs, there is a need to develop cost-effective and environmentally sustainable practices. Organic amendments increase the immediate availability of essential nutrients and enhance soil resilience to internal and exogenous stresses by reorganizing the soil structure.

Results and Discussion

Physical, chemical, nutritional, and biological indicators of soil health. Figure 1 illustrates the mean comparisons of SSI, CDR, and CROSS for different treatments across two experimental factors. The results indicate that all treatments, except for ES and BC in factor 1, resulted in a significant increase in SSI values compared to the control. Specifically, GP + VC > ES + VC > VC > BC > G > ES was the order of treatments that showed a significant increase in SSI. On the other hand, applying all treatment-factor combinations resulted in a significant decrease in CDR and CROSS values. The order of treatments that showed a significant decrease in CDR and CROSS values was GP + VC > ES + VC > GP > ES > VC > BC.

Among all treatments, the GP + VC and ES + VC treatments showed the highest increase in SSI and the greatest decline in CDR and CROSS values. The mean increase of 1.7 to 2.3 folds for SSI and the mean reduction of 1.9 to 2.2 folds and 1.7 to 2.1 folds for CDR and CROSS, respectively, were observed compared to the control. Lower CDR and CROSS values indicate higher soil aggregate stability. The results indicate that all treatments increased the stability of soil aggregate and improved soil structure as represented by greater SSI and lower CDR and CROSS values[6,16,26]. Quantified soil physical properties directly or indirectly represent energy and mass fluxes in the soil environment, which in turn determine plant growth and microbial activities[6,16]. The positive impact of GP and ES treatments on soil stability indices (i.e., SSI, CDR, and CROSS) can be significantly amplified in the presence of VC. The beneficial effect of VC on soil stability indices can be explained by additional SOC input by organic amendments, thereby promoting the flocculation of the individual soil particles into aggregates (Table 1)[15,27–29]. This process may overturn or decelerate the soil structural collapse stimulated by salts in saline-sodic soils. The negative correlations we found between OC and CDR ($r = 0.51$, <0.05) and OC and CROSS ($r = 0.49$, <0.05) confirm that SOC input by organic amendments is a key factor preventing clay dispersion and soil structural collapse. This result accords well with the findings of Pulido Moncada, et al.[26] and Abbas, et al.[30]. It is well known that the application of chemical amendments such as GP and ES preserves soil structural integrity through the substitution of Ca^{2+} for Na^{+} and increasing the concentration of electrolytes and the flocculation of clay colloids[7,12,16,28,31]. This process promotes the formation and stabilization of clay clusters[16,32]. Our results suggest that the incorporation of VC as organic amendment increases the effectiveness of GP and ES improving soil physical health in saline-sodic soils. The CDR (Table 2) was significantly correlated with the CROSS ($R^2 = 0.99$, $P < 0.001$), implying that indices can be used synonymously for assessing the soil structural quality in saline-sodic soils. Previous studies have also highlighted the negative impacts of salinization /sodification on soil physical health represented by CDR and CROSS values[33–35].

The results demonstrated that the combination of GP and ES treatments with VC had positive synergistic effects, as evidenced by improved values of SSI, CDR, and CROSS parameters. Previous research has attributed the positive feedback of chemical-organic synergy to the stimulation of clay flocculation through Ca^{2+} substitution for Na^{+} and an increased concentration of electrolytes[16,32]. Additionally, microbial inoculation was found to be more effective than non-inoculated treatments at improving soil physical properties, with statistically significant differences observed only for SSI (Fig. 1). This result may be linked to the organic compounds produced (e.g., organic acids, polysaccharides, and fungal mycelium) during the inoculation process by microorganisms. The organic compounds have been proved to enhance the binding between individual soil particles to form macroaggregates, thereby improving the SSI, CDR, and CROSS values[26,28].

Inoculated and non-inoculated treatments significantly increased the OM and CEC compared to the control, whereas combined treatments had a more pronounced effect on enhancing both parameters (Table 3). The increase of OM and CEC under combined treatments ranged from 2.2 to 2.4 folds (GP + VC) and 1.68 to 1.64 folds (ES + VC) for OM and 39.5 to 42.8% (GP + VC) and 33.9 to 35.7% (ES + VC) for CEC. The increase in OM could be explained by (a) the high organic C content of organic treatments (e.g., VC and BC) potentially enhancing SOC in the low OM soils (e.g., salt-affected soils) and (b) VC and BC generally show stimulating impacts on root growth and soil microorganism vitality[28,36]. The enhancement of OM and CEC is regarded as a significant benefit for soil health, since these parameters are critical for numerous soil physical, chemical, and biological functions and ecosystem services[6].

Applications of all inoculated and non-inoculated treatments largely regulated the salinity and sodicity indicators [pH, EC, SAR, exchangeable Na, and ESP] compared to the control (Table 3). Microbial inoculation further enhanced the efficacy of treatments in regulating the salinity/sodicity (Table 4). The reduction in pH, SAR, and ESP by inoculation ranged from 0.66 to 1.45 units, 97 to 186%, and 80 to 177%, respectively. These findings are consistent with

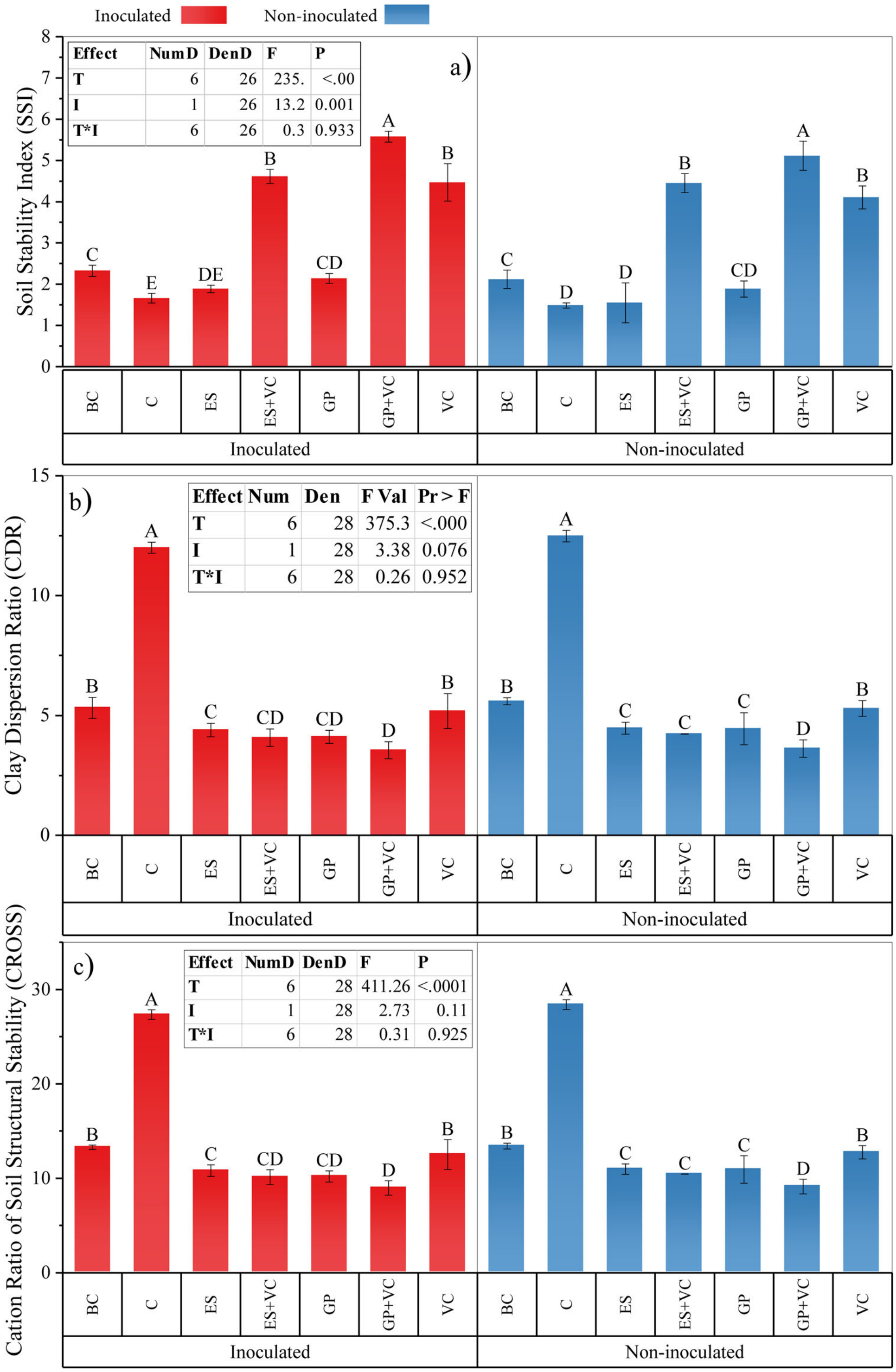

Fig. 1 Analysis of Variance and mean comparison of the physical soil health indicators. The physical soil health indicators are (**a**) SSI, (**b**) CDR, and (**c**) CROSS. T treatment, I inoculation, T*I treatment by inoculation interaction. Different letters within each factor represent the significant differences at $p < 0.05$ according to Fisher's LSD. The vertical error bars represent the standard deviation. Bars highlighted in red, and blue represent inoculated and non-inoculated treatment values, respectively.

prior research[37–39]. Among the individual and combined treatments, VC and GP + VC were the most effective in improving the sodicity indicators. This effect is likely related to (1) the release of Ca^{2+} from gypsum and vermicompost which are calcium-rich sources[40] and (2) the mobilization of insoluble carbonates (as supported by a significant drop in CCE) by organic acids and carbonic acid released by the decomposition of VC and subsequent increase in the concentration of Ca^{2+} and Mg^{2+}. These processes likely promoted the reactivity of Ca^{2+} and Mg^{2+} and replacement by the excess Na^{+} in the cation exchange sites. The result was notable reductions in all of pH, exchangeable Na, SAR, and ESP[7,41].

Additionally, all treatments reduced the mean value of EC by 64 to 142%. GP treatment alone and GP + VC treatment were most effective in reducing soil EC. The possible explanations are:

Table 2 Analytical methods for soil health indicators analyses and abbreviations.

Soil properties	Abbreviation	Protocol description and reference
Soil texture	–	Hydrometer method[75].
Soil stability index	SSI	Eq. (2)[67].
Cation ratio of soil structural stability	CROSS	Eq. (3)[33].
Clay dispersion ratio	CDR	Eq. (4)[76].
pH	pH	Determined in saturated paste using a glass electrode[68]
Electrical conductivity	EC	Determined in saturated paste extract using an EC meter[68].
Calcium carbonate equivalent	CCE	Titration with HCl[68].
Soil organic carbon	SOC	Potassium dichromate oxidation[68].
Cation exchangeable capacity	CEC	sodium acetate extraction at pH 8.2[68].
Total N	TN	Kjeldahl digestion-distillation approach[77].
Avaiable phosphorus	AP	Sodium bicarbonate extraction and colorimetric detection[78].
Available potassium	AK	Extracting with ammonium acetate and estimated by flame photometer[79].
Exchangeable sodium	ENa	Extracting with ammonium acetate and determined by flame photometer[68].
Soluble cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+})	–	Determined in saturated paste extract using complex-metric titration (Ca^{2+}, Mg^{2+}) flame photometer (Na^{+}, and K^{+})[68].
Available trace metals (Fe, Mn, Cu, and Zn)	–	Extracting with diethylene triamine pentaacetic acid (DTPA) and determined by atomic absorption spectrophotometer[80].
Sodium adsorption ratio	SAR	Eq. (5)[68].
Exchangeable sodium percentage	ESP	Eq. (6)[68].
Microbial biomass carbon	MBC	Chloroform-fumigation method[81].
Bacterial respiration	BR	Substrate-induced respiration technique using bactericide streptomycin sulfate[82].
Subestrat induced respiration	SIR	The method described by[83].
Carbon availability index	CAI	Eq. (7)[69].
Metabolic quotient	qCO_2	Eq. (8)[69].
Elemental Sulfur	ES	
Vermicompost	VC	
Biochar	BC	
Microbial inoculation	MI	
Linear Soil Health Index	L-SHI	
Nonlinear SHI	NL-SHI	
Principal Component Analysis	PCA	
Minimum dataset	MDS	
Totak dataset	TDS	

Table 3 Chemical soil health indicators of saline-sodic soils across treatments.

Experimental factor	Experimental tretment	pH	OM (%)	CCE	CEC (cmol kg^{-1})	EC (dS m^{-1})	SAR	ESP (%)	Na-Exch (cmol kg^{-1})
With MI	C	9.35 a	0.66 e	22.5 a	11.2 c	4.6 a	12.9 a	14.7 a	1.70 a
	GP	8.07 b	0.75 de	16.3 b	13.3 b	2.1 c	5.1 cd	6.4 b	0.88 c
	ES	8.04 b	0.86 de	16.7 b	13.1b	2.7 b	5.4 c	6.6 b	0.89 c
	VC	8.10 b	1.79 b	16.1 bc	15.1 a	2.1 c	6.2 b	6.0 bc	0.88 c
	BC	8.52 ab	0.93 c	17.5 b	13.4 b	2.8 b	6.2 b	7.3 b	0.98 b
	GP + VC	7.90 bc	2.23 a	14.2 d	16.0 a	1.9 d	4.5 e	5.3 e	0.80 e
	ES + VC	7.97 bc	1.77 b	15.8 c	15.2 a	2.0 d	4.9 cd	5.8 d	0.85 cd
Without MI	C	9.35 a	0.63 e	22.7 a	11.2 c	4.8 a	13.0 a	15.0 a	1.72 a
	GP	8.17 b	0.68 de	16.5 bc	12.8 b	2.3 c	5.4 c	6.6 c	0.90 c
	ES	8.23 b	0.72 de	17.3 b	13.1b	2.8 b	5.5 c	7.2 cd	0.91 c
	VC	8.30 b	1.64 b	16.2 bc	14.8 a	2.4 c	6.3 b	7.8 b	0.89 cd
	BC	8.69 a	0.85 cd	17.8 b	13.2 b	2.9 b	6.6 b	8.3 b	1.10 b
	GP + VC	7.93 bc	2.05 a	14.5 d	15.6 a	2.0 d	4.6 e	5.5 f	0.82 e
	ES + VC	8.03 bc	1.68 b	16.0 c	15.0 a	2.0 d	5.2 d	6.4 e	0.86 d

Na-Exch Na-Excgangeable, *GP* gypsum, *ES* elemental sulfur, *VC* vermicompost, *BC* biobhar, *MI* Microbial Inoculation. For each factor, different letters in each column show significant differences at $p < 0.05$ according to the Fisher's LSD.

(1) improvements in soil porosity and permeability due to the addition of soil amendments (e.g., GP and GP + VC) that enhanced the leaching of salts[16,36,42] and 2) adsorption of excess salts by organic treatments (e.g., VC). Other studies have shown similar trends in soil EC when organic amendments were used to remediate salt-affected soils[28,43].

Disregarding the microbial inoculation, a significant increase occurred in the total N, available P, and K under almost all amendments versus control. The magnitude of this increase ranged from 39–210%, 59–260%, and 10–49%, respectively (Table 5). The most effective macronutrient booster among the amendments was found to be the combined treatments, followed by individual organic treatments (i.e., VC and BC) and chemical treatments (i.e., GP and ES). This implies that the application of organic amendments, both individually and in combination with chemical treatments, had a greater impact on the enhancement of

Table 4 Effect of microbial inoculation on chemical health indicators of saline-sodic soils across treatments.

Soil chemical properties	Experimental factor	Treatment						
		C	GP	ES	VC	BC	GP + VC	ES + VC
pH	F1	9.4 ns	8.1 ns	8.0 ns	8.1 ns	8.5 ns	7.9 ns	8.0 ns
	F2	9.4	8.2	8.2	8.3	8.7	7.9	8.0
OM (%)	F1	0.66 ns	0.75 a	0.86 a	1.79 ns	0.93 ns	2.23 ns	1.77 ns
	F2	0.59	0.62 b	0.75 b	1.64	0.85	2.05	1.78
CCE (%)	F1	22.5 ns	16.3 ns	16.7 ns	16.1 ns	17.5 ns	14.2 ns	15.8 ns
	F2	22.7	16.5	17.3	16.2	17.8	14.5	16.0
CEC (cmol kg^{-1})	F1	11.6 ns	13.3 ns	13.1 ns	15.1 ns	13.4 ns	16.0 ns	15.2 ns
	F2	12.8	13.2	14.8	15.6	15.0	13.1	11.1
EC (dSm^{-1})	F1	4.6 ns	2.1 ns	2.7 ns	2.1 ns	2.8 ns	1.9 ns	2.0 ns
	F2	4.8	2.3	2.8	2.4	2.9	2.0	2.0
SAR	F1	12.9 ns	5.1 ns	5.4 ns	6.2 ns	6.2 ns	4.5 ns	4.9 ns
	F2	12.9	5.4	5.5	6.3	6.6	4.6	5.2
ESP (%)	F1	14.7 ns	6.4 ns	6.6 ns	6.0 ns	7.3 ns	5.3 ns	5.8 ns
	F2	15.0	6.6	7.2	7.8	8.3	5.5	6.4
EX-Na (cmol kg^{-1})	F1	1.70 ns	0.88 ns	0.89 ns	0.88 ns	0.98 ns	0.80 ns	0.85 ns
	F2	1.72	0.90	0.91	0.89	1.10	0.82	0.86

ns is the lack of significant difference. For each factor, different letters in each column show significant differences at $p < 0.05$ according to Fisher's LSD. *F1* with microbial inoculation, *F2* without microbial inoculation. ns; represents the lack of significat difference. *GP* gypsum, *ES* elemental sulfur, *VC* vermicompost, *BC* biochar. ns is the lack of significant difference.

Table 5 Nutritional indicators of health indicators of saline-sodic soils across treatments.

Experimental factor	Treatment	TN (%)	Available P	Available K	Fe- DTPA	Mn- DTPA	Zn- DTPA	Cu- DTPA
		mg kg^{-1}						
With microbial inoculation	C	0.036 e	6.6 e	155.6 d	2.6 d	3.0 d	0.50 e	0.18 e
	GP	0.055 d	10.5 d	196.8 bc	5.3 b	5.7 b	0.98 c	0.25 c
	ES	0.059 d	10.3 d	182.2 c	5.3 b	5.1 c	0.99 c	0.25 c
	VC	0.095 b	15.3 b	202.3 b	5.6 b	5.9 b	1.06 c	0.39 a
	BC	0.062 c	12.7 c	187.7 bc	4.7 c	5.0 c	0.89 d	0.21 d
	GP + VC	0.113 a	23.5 a	233.5 a	6.3 a	6.5 a	1.37 a	0.41 a
	ES + VC	0.102 b	21.6 a	228.9 a	6.0 a	6.3 a	1.12 b	0.33 b
Without microbial inoculation	C	0.036 e	6.0 e	154.8 d	2.4 d	3.0 d	0.39 f	0.18 e
	GP	0.050 d	10.0 d	170.6 c	4.0 b	5.1 b	0.86 d	0.23 c
	ES	0.055 c	10.1 d	160.6 c	4.0 b	4.4 c	0.88 d	0.20 d
	VC	0.090 b	14.4 b	185.6 b	4.2 b	5.2 b	0.95 c	0.33 b
	BC	0.059 c	12.6 c	165.6 c	3.5 c	4.5 c	0.74 e	0.20 d
	GP + VC	0.105 a	20.9 a	209.0 a	4.5 a	5.7 a	1.18 a	0.37 a
	ES + VC	0.095 b	18.9 a	206.5 a	4.6 a	5.4 a	1.05 b	0.33 b

For each factor, different letters in each column show significant differences at $p < 0.05$ according to Fisher's LSD. *GP* gypsum, *ES* elemental sulfur, *VC* vermicompost, *BC* biochar.

soil macronutrients. Total N concentration was highly correlated with soil organic carbon ($r = 0.95$, $P < 0.001$), indicating that increased SOC and TN were strongly tied to OM input from organic treatments. N cycling and SOC are intimately linked and therefore follow similar patterns[6]. As with TN, the increased amounts of available P and K were more evident for treatments containing increased OM. This is likely due to the addition of P and K by decomposing organic treatments and soil health improvement by the synergistic effect of organic and chemical amendments[44]. The application of GP and ES in isolation did not contribute to the soil's budget of P and K. However, previous studies have demonstrated that their use in combination with organic amendments can potentially enhance the availability of P that is sequestered by calcium carbonate and facilitate the placement of K in the exchangeable sites[45–47].

All treatments, regardless of inoculation, showed a significant impact on micronutrients (Table 6). The range of increase in micronutrients among treatments varied between 46 to 240%, 47 to 120%, 78 to 270%, and 12 to 130%, for Fe, Mn, Zn, and Cu, respectively. Microbial inoculation further increased the micronutrient concentrations in all treatments ($P < 0.05$) (Table 6). A possible explanation is the dissolution and release of micronutrients bonded to soil-native calcium carbonate in the presence of microbial metabolomics (e.g., organic acids). Previous studies have shown that microorganisms can secrete an abundance of organic acids when stressed by salinity and sodicity[48]. The rate of increase for Fe, Mn, and Zn was in the order of GP + VC > ES + VC > VC > GP > ES > BC and Cu followed the order of GP + VC ≈ VC > ES + VC > GP ≈ ES > BC (Table 5). These results show that treatments including VC and BC had the greatest and least effect on increasing micronutrients, respectively. Significant differences between VC and BC regarding the micronutrients release can be attributed to: (1) lower initial micronutrients level in BC (approximately half of those in vermicompost) (Table 1), (2) a greater effect of VC on favorable soil physicochemical conditions (e.g., decreasing clay dispersion, pH, SAR, and ESP) thereby indirectly improving soil fertility (Table 2 and Fig. 1), and (3) relatively lower decomposition rate

Table 6 Nutritional qualities of health indicators of saline-sodic soils across two factors.

Soil nutritionl properties	Factor	Treatment						
		C	GP	ES	VC	BC	GP + VC	ES + VC
TN (%)	F1	0.036 ns	0.055 ns	0.059 ns	0.095 a	0.062 a	0.113 a	0.102 a
	F2	0.036	0.050	0.055	0.09 b	0.059 b	0.105 b	0.095 b
Available P (mg kg−1)	F1	6.6 ns	10.5 ns	10.3 ns	15.3 ns	12.7 ns	23.5 a	21.5 a
	F2	6.0	10.0	10.1	14.4	12.6	20.9 b	18.9 b
Available K (mg kg−1)	F1	155.6 ns	196.8 a	182.2 a	202.3 a	187.7 a	233.5 a	228.9 a
	F2	154.8	170.6 b	160.6 b	185.6 b	165.6 b	209.0 b	206.5 b
Fe- DTPA (mg kg−1)	F1	2.6 ns	5.3 a	5.3 a	5.6 a	4.7 a	6.3 a	6.0 a
	F2	2.4	4.0 b	4.0 b	4.2 b	3.5 b	4.5 b	4.6 b
Mn- DTPA (mg kg−1)	F1	3.2 ns	5.9 a	5.1 a	5.7 a	5.0 a	6.5 a	6.3 a
	F2	3.0	5.2 b	4.4 b	5.1 b	4.5 b	5.7 b	5.4 b
Zn- DTPA (mg kg−1)	F1	0.50 a	0.98 a	0.99 a	1.06 a	0.89 a	1.37 a	1.12 a
	F2	0.39 b	0.86 b	0.88 b	0.95 b	0.74 b	1.18 b	1.05 b
Cu- DTPA (mg kg−1)	F1	0.19 ns	0.25 ns	0.25 ns	0.41 a	0.21 ns	0.44 a	0.35 ns
	F2	0.18	0.23	0.22	0.33 b	0.20	0.37 b	0.34

For each soil nutritional indicator, different letters in each column show significant differences at $p < 0.05$. ns; represents the lack of significant difference.

of BC than VC and incremental release of micronutrients. Other studies also suggest that the role of organic compounds in nutrient availability depends on chemical composition and decomposition rates[28,49].

Soil biological indicators including BR, SIR, MBC, CAI, and qCO2 demonstrated a positive and significant response to soil remediation practices (Fig. 2). The highest rate of BR, SIR, MBC, and CAI was found at VC + GP treated soil, followed by VC + ES ≥ VC > BC > GP > ES. This order confirms that the synergies in coupled organic-chemical amendments offer the greatest benefit to microbial activity. A similar trend was observed for most other physicochemical and nutritional indicators. This can be tied to SOC, which can stimulate the microflora and increase soil microbial abundance/biomass (e.g., BR, SIR, and MBC). SOC is a diverse energy source that directly controls the microorganism activity and abundance[47,50]. Indirectly, organic amendments may increase microbial abundance and metabolites due to i) decreasing salinity and sodicity stress on microbes[15,16,51], ii) improved soil aeration and water permeability[42,47], iii) improved water retention and supply to microorganisms[42,52], and iv) increased root exudation of dissolved organic carbon and nitrogen containing compounds which are the major constituents of microbial biomass[11,47]. Clearly, SOC has a remarkable capacity to alleviate stress on plants and biota, particularly in saline and sodic soils, where it maintains soil vitality and functions[6]. Treatments subjected to microbial inoculation were 14 to 34% ($p < 0.05$) more effective in improving soil biological health (Fig. 2). These results show that microbial inoculation promotes the population and activity of soil microorganisms which is consistent with previous studies[11,42].

Soil health index. Soil Health Index was calculated using both linear and nonlinear scoring functions for all treatments. All soil physical, chemical, nutritional, and biological health indicators were subjected to PCA analysis for dimensionality reduction to determine the MDS dataset. As presented in Table S1, about 84.6% of the total variance of data was explained by four principal components (PCs) with eigenvalues > 1 and variance > 5%. The first PC, which explained 41.2% of the variability, was associated with EC, ESP, calcium carbonate, total N, available P and K, and micronutrients. There was a high correlation ($P < 0.01$) between EC with ESP, calcium carbonate, available Fe, Mn, and Zn as well as between available K with total N, available P and Cu, and BR. Therefore, only EC and available K having the greatest coefficients were selected from PC1 as potential indicators for the MDS. OM, pH, CAI, and SSI are the highly weighted indicators in PC2 that explained 22.6% of the total variance. OM had significant correlation with CAI and SSI ($p < 0.01$), but not with total pH. Therefore, OM with the greatest coefficient (0.90) and pH were maintained in the MDS dataset. PC3 and PC4, explained 13.7 and 7.1% of the total variance, respectively. Exchangeable Na from PC3 and SIR from PC4 were included in the MDS data set for the SHI evaluation. Thus, 6 out of the 23 initial soil health indicators including EC, available K, OM, pH, exchangeable Na, and SIR were included in the final MDS dataset. The selected properties reflected a coherent inclusion of soil chemical (e.g., pH, EC, exchangeable Na), nutritional (e.g., OM and available K), and microbial (e.g., SIR) properties.

The mean relative contribution of the selected variables to the calculated SHI followed the order: EC and available K (49%) > OM and pH (27%) > exchangeable Na (16%) > SIR (8%). EC along with available K, and SIR had the highest and lowest weight, resulting in the highest and the lowest contributions to the SHI, respectively (Table S2). Among the 23 soil health indicators, EC, K, OM, and pH were identified as the primary soil health indicators, representing 76% of the overall SHI values. This result is expected given the key impact of these indicators on multiple soil-plant functions, particularly soil nutritional, microbial community and activity, and plant productivity[6]. OM plays a key role in soil aggregation, structural stability, nutrient supply, microbial proliferation, and agroecosystem resilience[53,54]. Similarly, EC is a key indicator of soluble salt concentration, nutrient cycling and microbial activity, particularly relevant in saline and sodic soils[55].

Regardless of microbial inoculation, all treatments led to significant improvements in both the L-SHI (with a mean increase of 12% to 91%) and NL-SHI (with a mean increase of 44% to 134%) compared to the control. The most significant enhancement was observed in the synergistic approach (Fig. 3). The findings are consistent with previous studies[56,57]. They reported a significant increase in SHI between 37% and 138% after applying organic amendments to semi-arid soils in India and Turkey. The results show that the combination of VC with chemical amendments was more effective in improving soil health, with the optimal sequence of VC + GP > VC + ES > VC > GP > BC > ES. The outstanding performance of the combined treatments can be attributed to the positive impact of VC on soil fertility and plant productivity. This effect was amplified by

Effect	Treatment	Num DF	Den DF	F Value	Pr > F
T		6	28	63.42	<.0001
I	*BR*	1	28	12.99	0.001
T*I		6	28	0.92	0.494
T		6	28	46.71	<.0001
I	*SIR*	1	28	402.82	<.0001
T*I		6	28	1.05	0.414
T		6	12	397.32	<.0001
I	*MBC*	1	14	190.43	<.0001
T*I		6	14	5.57	0.004
T		6	28	48.1	<.0001
I	*CAI*	1	28	8.85	0.006
T*I		6	28	0.52	0.791
T		6	1	35.82	0.127
I	*qCO2*	1	1	3.46	0.314
T*I		6	1	0.38	0.842

Fig. 2 Analysis of Variance and means comparison of the biological soil health indicators across inoculated and non-inoculated treatments. The biological soil health indicators are (**a**) BR, (**b**) SIR, (**c**) MBC, (**d**) CAI, and (**e**) qCO_2. T treatment, I inoculation, T*I treatment by inoculation interaction. Different letters within each factor represent the significant differences at $p < 0.05$ according to Fisher's LSD. The vertical error bars represent the standard deviation. Bars highlighted in purple, and orange represent inoculated and non-inoculated treatment values, respectively.

increased accumulation of Ca^{+2} from GP and ES treatments and subsequent removal of Na^{+} from exchangeable sites. This process improved several soil properties (e.g., pH, SAR, and ESP) that are incorporated into the SHI index[42,44]. Vermicompost is a nutrient-rich biological soil conditioner that contains large amounts of organic and humic substances that stimulate the activity of the soil microbial community[15,58]. The enhanced SOC input to salt-affected soil through VC application improved soil aggregation, CEC, pH, and salt leaching potential. The cumulative result was a reduced effect of salinization and sodification, improved SHI, and ultimately improved plant growth[30,42,58,59]. Therefore, VC + GP/ES can be considered as an environmentally sustainable and cost-effective amendment to improve the health of saline-sodic soils and promoting plant growth and productivity.

Compared to non-inoculated treatments, all inoculated treatments improved SHI by 2 to 15% and 4 to 16% for L-SHI and NL-SHI, respectively, although these changes were not statistically significant in most treatments (Fig. 3). The mean NL-SHI values for all treatments (0.52–0.54) remained below mean L-SHI values (0.47–0.66), being consistent with previous studies[53,54,57]. However, NL-SHI scores demonstrated greater sensitivity (2.43 to 2.60) to the numerical changes in parameters than L-SHI (1.69 to 2.05) (Table S2), suggesting that the SHI from non-linear scoring approach better represents the soil functions than the linear method[53]. A practical SHI is required to be sensitive enough to detect the effects of management and remediation practices on soil health and functions[54,60].

Both L-SHI and NL-SHI were significantly related to wheat growth attributes including wet and dry biomass weight, and root length and volume (Fig. 4). This implies that improvement in soil health parameters coincides with greater roots and shoots development in wheat crop. The significant association of SHI

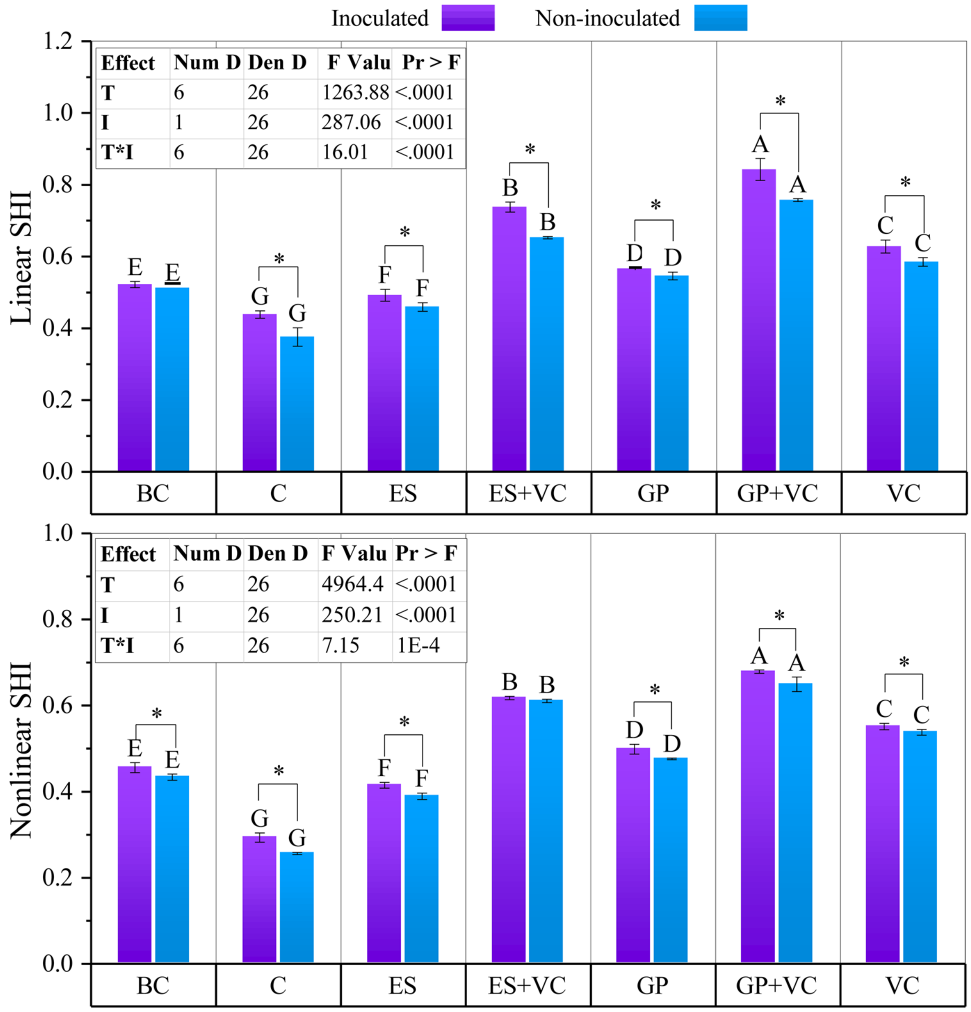

Fig. 3 Analysis of Variance and mean comparison of linear and nonlinear SHI scores across inoculated and non-inoculated treatments. Letter groups demonstrate the significance of differences among amendments within inoculated and non-inoculated groups. T treatment, I inoculation T*I treatment by inoculation interaction. * represents the significance of difference between inoculated and non-inoculated sets of each amendment at $p < 0.05$ according to Fisher's LSD. The vertical error bars represent the standard deviation.

to wheat growth parameters may be related to the rigorous process to select most meaningful soil health indicators[53,61]. Correspondence of pH, EC, OM and nutrients with SHI and crop growth has been found by other research in salt-affected soils[15,28,57]. We also found that 29 to 87% of the variance in the computed SHIs (Fig. 4) can be explained using the wheat growth data, substantiating the strong effect of SHI on wheat growth following the application of amendments in saline-sodic soils. Overall, according to coefficients of determination, NL-SHI model was more accurate than the L-SHI model in predicting the wheat growth and biomass production[53,57]. This may be explained by the fact that the nonlinear scoring methods require a more in-depth understanding of each indicator's function within the soil-crop system[53,62].

Materials and methods

Study region and field campaign. Composite soil samples comprising five sub-samples were collected from 0 to 20 cm soil depth from the natural environment of suburban Urmia city (37°22′58.2″ N, 45°15′44.05″ E) in West Azerbaijan Province, Northwestern Iran. The sampling area represents large areas of saline-sodic soils in the Urmia plain. Study region has a semi-arid climate with mean annual precipitation of ~330 mm and mean annual temperature of ~13 °C. The altitude and prevalent land slope are 1300 m and 0 to 2%, respectively. The soils of the region are predominantly originated from calcareous alluvial sediments and were generally classified as Sodic Calcixerepts and Calcic Solonetz according to the Key Soil Taxonomy[63] and WRB system[64], respectively. The soil texture is loam with a fractional composition of 50, 30, and 20% of sand, silt and clay particles, respectively. The baseline soil analysis revealed high values of pH, calcium carbonate, EC, and SAR, moderate CEC, and low OM and micronutrients (Fe, Mn, Zn, and Cu) (Table 1).

Experimental design. In 2021, a greenhouse experiment was conducted at the Department of Soil Science in Urmia University, Iran, to investigate the effects of various remediation treatments and microbial inoculation on soil quality. The study employed a Randomized Complete Block Design (RCBD) with factorial treatments, where factor 1 comprised seven remediation treatments with microbial inoculation (T + MI) and factor 2 comprised the same treatments without microbial inoculation (T-MI), both with three replications. The seven treatments included a control (C), gypsum (GP), elemental sulfur (ES), vermicompost (VC), biochar (BC), gypsum + vermicompost (GP + VC), and elemental sulfur + vermicompost (ES + VC), which were assigned to each of the two factors. VC and BC were applied at a rate of 90 kg ha^{-1}. The BC was produced through pyrolysis of grape wood at an early stage of combustion at 400 °C in a partially anoxic state. On the other hand, VC was produced using plant residues, specifically deciduous leaves, and cow manure as feed for worms at 80% moisture content[65]. The chemical characteristics of biochar and vermicompost is presented in Table 1. The amount of GP and ES were applied to soil at the rate of 2.0 and 0.4 g kg^{-1}, respectively, is estimated according to the gypsum requirements (GR) as follows:

$$GR = \left(\frac{ESP_1 - ESP_2}{100}\right) \times CEC \quad (1)$$

where ESP_1 and ESP_2 are the initial value (20.2%) and the desired value (8%) of the exchangeable sodium percentage, respectively, and CEC is the cation exchangeable capacity (cmol kg^{-1}). Gypsum had pH, 7.0; EC 2.0 dS m^{-1}; and solubility, 2.8 g L^{-1}.

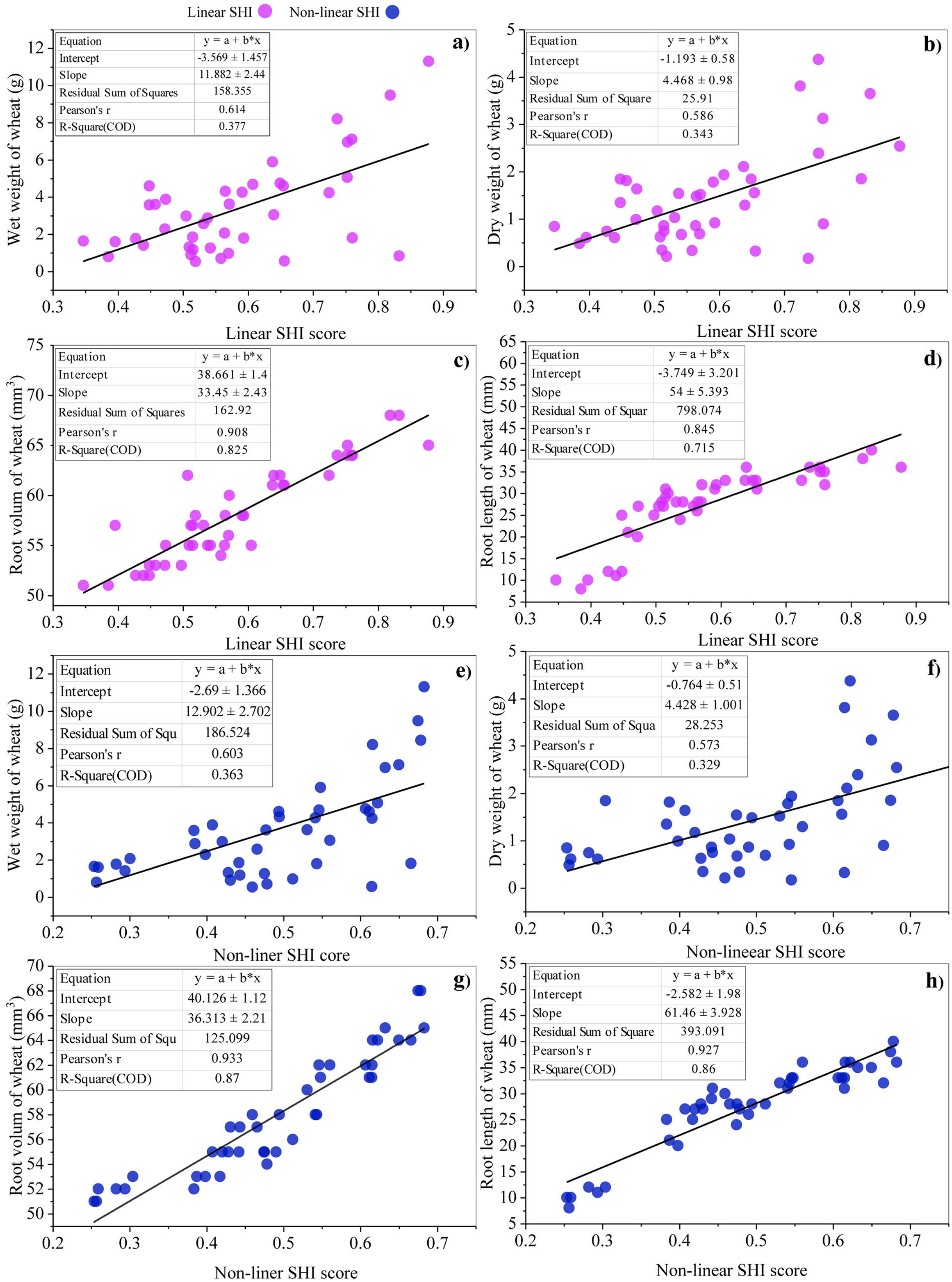

Fig. 4 The linear regression analysis of the relationship between linear and nonlinear SHI scores and wheat growth parameters. Linear (**a**–**d**) and nonlinear (**e**–**h**) SHI scores are represented by pink and blue colors, respectively.

Soil incubation and leaching column study. The study involved mixing each treatment with soil fractions in separate plastic bags and incubating the resulting soil in covered plastic containers at a temperature of 25–27 °C and a humidity of 32.0–36.0% for a period of 5 months at field capacity moisture content. The incubated soils were then uniformly packed into leaching columns consisting of PVC cylinders with a length of 40 cm and an inner diameter of 20 cm. Acid-washed sand with a particle size of less than 0.2 mm was placed at the bottom of each cylinder to a height of 2.5 cm to hold the soil. The soil was then uniformly packed into the cylinder for each treatment to prevent air pockets and to achieve a bulk density of 1.3 g cm^{-3} that represented field conditions. A ~0.25 cm layer of acid-washed sand and a thin piece of sponge were placed on the soil surface to prevent sealing and water distribution disruption. A cheesecloth was attached to the outlet to hold the sample during the experiment[37,43]. The soil cylinders were slowly and gradually saturated by capillary motion from the bottom along with the gradual and incremental raise of the reservoir. Then a steady-state water flow was initiated by supplying water from the top and collecting the effluent fractions by a continuous supply of pore water by a Marriott device. EC and SAR were measured regularly following collection of each pore water unit. The leaching process continued until the effluent stabilized and the cumulative pore volume was calculated once EC and SAR dropped below the critical levels (EC < 4 dS m^{-1}, SAR < 13). During the draining process, the concentration of soluble salts per volume of pore water was measured in effluent and the breakthrough curve for each soil was drawn. The breakthrough curve indicates changes in salts concentration during the washing process. It can help predict optimal leaching volume to achieve the optimal salt concentration. The salt leaching process in the columns was simulated using CTRAN software. After the column experiment, an average of 0.36 leaching requirement for all treatments was calculated. This coefficient was considered at each stage of wheat plant irrigation during its pot cultivation.

Pot experiment. After the column experiment, the experimental material was transferred to 3-kg pots. To maintain a consistent bulk density, we placed the same weight of soil in a fixed volume pot. A total of 42 pots were studied in a greenhouse setting for 150 days. In each pot, ~20 spring wheat seeds were planted and about 2 weeks after planting, 5 seedlings were maintained in each pot. Microbial inoculum with a concentration of 2% and minimum bacterial population of 108 CFU per gram incorporated with the seeds of all treatments of factor 1 (with microbial inoculation). To prepare the microbial treatments, Pseudomonas fluoresces (Accession number in GenBank is MW063588 based on 16 S rRNA gene sequencing) was used. Given previous studies[66], these bacteria were isolated from salt-affected soils around Lake Urmia and screened based on plant-growth promoting properties, including indole acetic acid, hydrogen cyanide, siderophore and exopolysaccharide. The bacteria were cultured in a nutrient broth medium to achieve a colony-forming unit (CFU)/mL value of 108.

The seeds were inoculated with bacteria by immersing and shaking for 2 h in the inoculant with microbial populations of 10-8 cells per mL. After shaking, the seeds were spread and dried under sterile airflow of a laminar hood and sown the same day. We added the explanations to the revised manuscript linesAll pots were irrigated regularly to near field capacity moisture content. Soil in pots was fertilized with superphosphate ($Ca(H_2PO_4)$ $2.H_2O$) at a rate of 0.75 g per pot during the soil preparation as well as by 1 g N per pot from urea (CH_4N_2O) three times during the potting cultivation period. Five months after planting, the plants were harvested, their root length and diameter were measured and the dry matter yield per pot was weighed. Soil samples from the pots were collected, air-dried and passed through a 2-mm mesh sieve.

Soil analysis. Soil samples collected from all pots were analyzed for physical, chemical, and biological properties. The physical attributes included the sand, silt, and clay contents, soil stability index (SSI), the cation ratio of soil structural stability (CROSS), and clay dispersion ratio (CDR). The chemical attributes included pH, EC, calcium carbonate equivalent (CCE), soil organic carbon (SOC), CEC, total N, available P and K, exchangeable Na^+, soluble cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+), the bioavailable fraction of trace metals (Fe, Mn, Cu, Zn), SAR, and ESP. The biological attributes included microbial biomass carbon (MBC), bacterial respiration (BR), substrate-induced respiration (SIR), metabolic quotients (qCO_2), microbial quotient (qM), and carbon availability index (CAI). The detailed analytical methods for soil analyses are presented in Table 2.

The SSI, CROSS, and CDR were respectively calculated using Eqs. (2), (3), and (3) as follows:[6,33,67]

$$SSI = \frac{1.72 \times OC}{P_C \times P_{Si}} \times 100 \quad (2)$$

$$CROSS = \frac{Na^+ + 0.56K^+}{\sqrt{\frac{(Ca^{2+} + 0.6Mg^{2+})}{2}}} \quad (3)$$

$$CDR = \frac{Clay_w}{Clay_c} \quad (4)$$

where OC, P_C, and P_{Si} are the percentage of organic carbon, clay, and silt, respectively. In Eq. (3), the concentrations of Na, K, Ca, and Mg are expressed in millimoles of charge L^{-1}. In Eq. (4), $Clay_w$ and $Clay_c$ are clay content in water-dispersed and Calgon-dispersed samples, respectively.

Following equations were used to calculate SAR and ESP:[68]

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}} \quad (5)$$

$$ESP = \frac{Na}{CEC} \times 100 \quad (6)$$

In Eq. (5), Na^+, Ca^{2+}, and Mg^{2+} are in meq l^{-1} and in Eq. (6), Na and CEC are in cmol kg^{-1}.

The biological indices, CAI and qCO2 were calculated by Eqs. (7) and (8), respectively[69].

$$CAI = \frac{BR}{SIR} \quad (7)$$

$$qCO_2 = \frac{BR}{MBC} \quad (8)$$

where BR, SIR, MBC, and OC represent bacterial respiration (mg CO_2-C kg^{-1} soil day^{-1}), substrate-induced respiration (mg CO_2-C kg^{-1} soil day^{-1}), microbial biomass carbon (mg CO_2-C kg^{-1} soil), and organic carbon (mg C kg^{-1} soil), respectively.

Soil health index. The Soil Health Index (SHI) was computed for all treatments of both factors 1 and 2 using both linear and nonlinear techniques in accordance with a four-step process outlined in previous studies[53,62,70]. The steps involved: (A) identification of a representative Minimum Data Set (MDS) by means of a factor analysis of variables in the Total Data Set (TDS); (B) assignment of scores to soil variables (ranging from 0 to 1) in accordance with standard scoring functions; (C) determination of weights for each soil variable through Principal Component Analysis (PCA); and (D) integration of variable scores into a weighted additive SHI.

To establish the MDS, the TDS dataset underwent Principal Component Analysis (PCA) to identify the most indicative variables. The principal components (PCs) exhibiting eigenvalues greater than one and explaining at least 5% of the total variance of the dataset were deemed suitable indicators. Within each PC, solely soil indicators with loading values within 10% of the highest factor loading were considered fundamental indicators[71,72]. In cases where several variables existed within a PC, correlation analysis among the factors determined which variables to eliminate as redundant. The MDS variables were then transformed into dimensionless scores ranging from 0 to 1 utilizing standard linear and nonlinear scoring function methods[55,62].

For linear scoring, Eqs. (10) and (11) were used for 'more is better' group variables and 'less is better' group variables, respectively:[53,72,73]

$$SL = \frac{X_i - M_i}{M_a - M_i} \quad (9)$$

$$SL = \frac{M_a - X_i}{M_a - M_i} \quad (10)$$

where SL is the linear score of soil indicator (ranging between 0 and 1), X_i is the soil indicator value, and M_i and M_a are the minimum and maximum values, respectively, for a given soil indicator.

For nonlinear scoring, a sigmoidal function [Eq. (12)] was fitted[74].

$$NSL = \frac{a}{1 + \left(\frac{X}{X_m}\right)^b} \quad (11)$$

where NSL is the non-linear score of the soil indicator (ranging from 0 to 1), a is the maximum score ($a = 1$) reached by the function, X is the value of selected soil indicator, X_m is the mean content of each soil indicator, and b is the slope; b values were set to −2.5 for 'more is better' and 2.5 for the 'less is better' curves.

Lastly, the linear SHI (SHI-L) and nonlinear SHI (SHI-NL) values were calculated, using the following models [Eqs. (13) and (14)]:[62]

$$SHI - L = \sum_{n=1}^{n} W_i \times LS_i \quad (12)$$

$$SHI - NL = \sum_{n=1}^{n} W_i \times NLS_i \quad (13)$$

where LS_i and NLS_i are the linear and nonlinear scores, respectively, W_i is the weighting coefficient of soil indicators derived from the factor analysis, and n is the number of selected soil health indicators using the MDS.

Statistical analysis. Analysis of Variance (ANOVA) was conducted and least squares means were separated using Duncan's significant difference test at 5% confidence interval. PCA was used to reduce multidimensionality in the dataset and select the most appropriate soil indicators for assessing SHI. For PCA, Kaiser–Meyer–Olkin test and Bartlett's test of sphericity were used to assess the capability of PCA to accurately sort down the soil health indicators for factor analysis. All data analyses and statistical tests were performed in SPSS (ver., 16.0, SPSS Inc.,).

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets relevant to the current study are available at https://zenodo.org/record/8129485.

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References

1. Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A. & Lombi, E. Soil and the intensification of agriculture for global food security. *Environ. Int.* **132**, 105078 (2019).
2. Hossain, M. S. Present scenario of global salt affected soils, its management and importance of salinity research. *Int. Res. J. Biol. Sci* **1**, 1–3 (2019).
3. Ivushkin, K. et al. Global mapping of soil salinity change. *Remote Sensing Environ.* **231**, 111260 (2019).
4. Shahid, S. A., Zaman, M. & Heng, L. (eds.) in *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques* 43–53 (Springer, 2018).
5. Puy, A., Lo Piano, S. & Saltelli, A. Current models underestimate future irrigated areas. *Geophys. Res. Lett.* **47**, e2020GL087360 (2020).
6. Weil, R. R. & Brady, N. C. *The Nature and Properties of Soils*. 15th ed (Pearson Education Inc, 2017).
7. Rezapour, S. & Kalashypour, E. Effects of irrigation and cultivation on the chemical indices of saline–sodic soils in a calcareous environment. *Int. J. Environ. Sci. Technol.* **16**, 1501–1514 (2019).
8. Rezapour, S., Kalashypour, E. & Asadzadeh, F. Assessment of the quality of salt-affected soils after irrigation and cultivation in semi-arid condition. *Int. J. Environ. Res.* **11**, 301–313 (2017).
9. Zhao, S. et al. Long-term effects of cattle manure application on the soil aggregate stability of salt-affected soil on the Songnen Plain of North-Eastern China. *J. Soils. Sediments* **23**, 1–11 (2022).
10. Qadir, M. & Schubert, S. Degradation processes and nutrient constraints in sodic soils. *Land Degradation Dev.* **13**, 275–294 (2002).
11. Sahab, S. et al. Potential risk assessment of soil salinity to agroecosystem sustainability: Current status and management strategies. *Sci. Total Environ.* **764**, 144164 (2021).
12. Arora, S., Singh, A. K. & Singh, Y. P. *Bioremediation of Salt Affected Soils: an Indian Perspective* (Springer, 2017).
13. Frenken, K. Irrigation in the Middle East region in figures AQUASTAT Survey-2008. *Water Reports* (2009).
14. FAO. *Food and Agriculture Organization of the United Nations (FAO)* (FAO, 2008).
15. Ding, Z. et al. A vermicompost and deep tillage system to improve saline-sodic soil quality and wheat productivity. *J. Environ. Manag.* **277**, 111388 (2021).
16. Kim, Y.-J., Choo, B.-K. & Cho, J.-Y. Effect of gypsum and rice straw compost application on improvements of soil quality during desalination of reclaimed coastal tideland soils: ten years of long-term experiments. *Catena* **156**, 131–138 (2017).
17. Seleiman, M. F. & Kheir, A. M. Maize productivity, heavy metals uptake and their availability in contaminated clay and sandy alkaline soils as affected by inorganic and organic amendments. *Chemosphere* **204**, 514–522 (2018).
18. Li, H., Zhao, Q. & Huang, H. Current states and challenges of salt-affected soil remediation by cyanobacteria. *Sci. Total Environ.* **669**, 258–272 (2019).
19. Leogrande, R. & Vitti, C. Use of organic amendments to reclaim saline and sodic soils: a review. *Arid Land Res. Manag.* **33**, 1–21 (2019).
20. Stavi, I., Thevs, N. & Priori, S. Soil salinity and sodicity in drylands: a review of causes, effects, monitoring, and restoration measures. *Front. Environ. Sci.* **9**, 712831 (2021).
21. Mao, X. et al. Remediation of organic amendments on soil salinization: Focusing on the relationship between soil salts and microbial communities. *Ecotoxicol. Environ. Safety* **239**, 113616 (2022).
22. Basak, N. et al. Assessing soil quality for rehabilitation of salt-affected agroecosystem: a comprehensive review. *Front. Environ. Sci.* **10**, 935785 (2022).
23. Nan, J. et al. Impact of flue gas desulfurization gypsum and lignite humic acid application on soil organic matter and physical properties of a saline-sodic farmland soil in Eastern China. *J. Soils Sediments* **16**, 2175–2185 (2016).
24. Zhou, M. et al. Additional application of aluminum sulfate with different fertilizers ameliorates saline-sodic soil of Songnen Plain in Northeast China. *J. Soils Sediments* **19**, 3521–3533 (2019).
25. Sheoran, P. et al. 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.* **243**, 106492 (2021).
26. Pulido Moncada, M., Gabriels, D., Cornelis, W. & Lobo, D. Comparing aggregate stability tests for soil physical quality indicators. *Land Degradation Dev.* **26**, 843–852 (2015).
27. Wang, L. et al. Application of organic amendments to a coastal saline soil in north China: effects on soil physical and chemical properties and tree growth. *PLoS ONE* **9**, e89185 (2014).
28. Zhang, X. et al. Biochar addition combined with daily fertigation improves overall soil quality and enhances water-fertilizer productivity of cucumber in alkaline soils of a semi-arid region. *Geoderma* **363**, 114170 (2020).
29. Verheijen, F. G. et al. The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. *Geoderma* **347**, 194–202 (2019).
30. Abbas, F., Lin, F., Zhu, Z. & An, S. A Novel Index (RI) to evaluate the relative stability of soils using ultrasonic agitation. *Sustainability* **13**, 4229 (2021).
31. Li, X., Wang, D., Ren, Y., Wang, Z. & Zhou, Y. Soil quality assessment of croplands in the black soil zone of Jilin Province, China: Establishing a minimum data set model. *Ecol. Indicators* **107**, 105251 (2019).
32. Mahmoodabadi, M. & Heydarpour, E. Sequestration of organic carbon influenced by the application of straw residue and farmyard manure in two different soils. *Int. Agrophys.* **28**, 169–176 (2014).
33. Rengasamy, P. & Marchuk, A. Cation ratio of soil structural stability (CROSS). *Soil Res.* **49**, 280–285 (2011).
34. Zhu, Y., Ali, A., Dang, A., Wandel, A. P. & Bennett, J. M. Re-examining the flocculating power of sodium, potassium, magnesium and calcium for a broad range of soils. *Geoderma* **352**, 422–428 (2019).
35. Emami, H., Astaraei, A. R., Fotovat, A. & Khotabaei, M. Effect of soil conditioners on cation ratio of soil structural stability, structural stability indicators in a sodic soil, and on dry weight of maize. *Arid Land Res. Manag.* **28**, 325–339 (2014).
36. Xie, W. et al. Effects of straw application on coastal saline topsoil salinity and wheat yield trend. *Soil Tillage Res.* **169**, 1–6 (2017).
37. Chaganti, V. N., Crohn, D. M. & Šimůnek, J. Leaching and reclamation of a biochar and compost amended saline–sodic soil with moderate SAR reclaimed water. *Agric. Water Manag.* **158**, 255–265 (2015).
38. Alcívar, M., Zurita-Silva, A., Sandoval, M., Muñoz, C. & Schoebitz, M. Reclamation of saline–sodic soils with combined amendments: impact on quinoa performance and biological soil quality. *Sustainability* **10**, 3083 (2018).
39. Schultz, E., Chatterjee, A., DeSutter, T. & Franzen, D. Sodic soil reclamation potential of gypsum and biocharadditions: influence on physicochemical properties and soil respiration. *Commun. Soil Sci. Plant Anal.* **48**, 1792–1803 (2017).
40. Sheikhi Shahrivar, F. & Khademi, H. Effect of gypsum on potassium and iron release from phlogopite to alfalfa. *J. Plant Nutrition* **41**, 509–519 (2018).
41. Sappor, D. K., Osei, B. A., & Ahmed, M. R. Reclaiming Sodium Affected Soil: The Potential of Organic Amendments. *International Journal of Plant & Soil Science*. **16**, 1–11 (2017).
42. Liu, M., Wang, C., Liu, X., Lu, Y. & Wang, Y. Saline-alkali soil applied with vermicompost and humic acid fertilizer improved macroaggregate microstructure to enhance salt leaching and inhibit nitrogen losses. *Appl. Soil Ecol.* **156**, 103705 (2020).
43. Sundha, P. et al. Can conjunctive use of gypsum, city waste composts and marginal quality water rehabilitate saline-sodic soils? *Soil Tillage Res.* **200**, 104608 (2020).
44. Rezapour, S. Effect of sulfur and composted manure on SO4-S, P and micronutrient availability in a calcareous saline–sodic soil. *Chem. Ecol.* **30**, 147–155 (2014).
45. Griffin, D. E., Wang, D., Parikh, S. J. & Scow, K. M. Short-lived effects of walnut shell biochar on soils and crop yields in a long-term field experiment. *Agric. Ecosyst. Environ.* **236**, 21–29 (2017).
46. Yazdanpanah, N., Pazira, E., Neshat, A., Mahmoodabadi, M. & Sinobas, L. R. Reclamation of calcareous saline sodic soil with different amendments (II): Impact on nitrogen, phosphorous and potassium redistribution and on microbial respiration. *Agric. Water Manag.* **120**, 39–45 (2013).
47. Dahlawi, S., Naeem, A., Rengel, Z. & Naidu, R. Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Sci. Total Environ.* **625**, 320–335 (2018).
48. Ullman, W. J., Kirchman, D. L., Welch, S. A. & Vandevivere, P. Laboratory evidence for microbially mediated silicate mineral dissolution in nature. *Chem. Geol.* **132**, 11–17 (1996).

49. Clark, G., Dodgshun, N., Sale, P. & Tang, C. Changes in chemical and biological properties of a sodic clay subsoil with addition of organic amendments. *Soil Biol. Biochem.* **39**, 2806–2817 (2007).
50. Zheng, H. et al. Enhanced growth of halophyte plants in biochar-amended coastal soil: roles of nutrient availability and rhizosphere microbial modulation. *Plant Cell Environ.* **41**, 517–532 (2018).
51. Rezapour, S., Samadi, A., Kalavrouziotis, I. K. & Ghaemian, N. Impact of the uncontrolled leakage of leachate from a municipal solid waste landfill on soil in a cultivated-calcareous environment. *Waste Manag.* **82**, 51–61 (2018).
52. Ajayi, A. E. & Rainer, H. Biochar-induced changes in soil resilience: effects of soil texture and biochar dosage. *Pedosphere* **27**, 236–247 (2017).
53. Mamehpour, N., Rezapour, S. & Ghaemian, N. Quantitative assessment of soil quality indices for urban croplands in a calcareous semi-arid ecosystem. *Geoderma* **382**, 114781 (2021).
54. Raiesi, F. & Beheshti, A. Evaluating forest soil quality after deforestation and loss of ecosystem services using network analysis and factor analysis techniques. *Catena* **208**, 105778 (2022).
55. Yeilagi, S., Rezapour, S. & Asadzadeh, F. Degradation of soil quality by the waste leachate in a Mediterranean semi-arid ecosystem. *Sci. Rep.* **11**, 1–12 (2021).
56. Sharma, K. et al. Effect of soil and nutrient-management treatments on soil quality indices under cotton-based production system in rainfed semi-arid tropical vertisol. *Commun. Soil Sci. Plant Anal.* **42**, 1298–1315 (2011).
57. Bilgili, A. V. et al. The effects of biochars produced from the residues of locally grown crops on soil quality variables and indexes. *Geoderma* **345**, 123–133 (2019).
58. Song, X., Li, H., Song, J., Chen, W. & Shi, L. Biochar/vermicompost promotes Hybrid Pennisetum plant growth and soil enzyme activity in saline soils. *Plant Physiol. Biochem.* **183**, 96–110 (2022).
59. Di, W. et al. Biochar combined with vermicompost increases crop production while reducing ammonia and nitrous oxide emissions from a paddy soil. *Pedosphere* **29**, 82–94 (2019).
60. Bünemann, E. K. et al. Soil quality—a critical review. *Soil Biol. Biochem.* **120**, 105–125 (2018).
61. Rezapour, S., Nouri, A., Jalil, H. M., Hawkins, S. A. & Lukas, S. B. Influence of treated wastewater irrigation on soil nutritional-chemical attributes using soil quality Index. *Sustainability* **13**, 1952 (2021).
62. Andrews, S. S., Karlen, D. & Mitchell, J. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agric. Ecosyst. Environ.* **90**, 25–45 (2002).
63. Staff, S. *Illustrated Guide to Soil Taxonomy* 372 (US Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, 2015).
64. IUSS Working Group WRB. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome (2015).
65. Gong, X. et al. Green waste compost and vermicompost as peat substitutes in growing media for geranium (Pelargonium zonale L.) and calendula (Calendula officinalis L.). *Scientia Horticulturae* **236**, 186–191 (2018).
66. Rouydel, Z. et al. Harnessing the potential of symbiotic endophytic fungi and plant growth-promoting rhizobacteria to enhance soil quality in saline soils. *Processes* **9**, 1810 (2021).
67. Pieri, C. J. *Fertility of Soils: A Future for Farming in the West African Savannah*. Vol. 10 (Springer Science & Business Media, 2012).
68. Sparks, D. L., Page, A. L., Helmke, P. A. & Loeppert, R. H. *Methods of Soil Analysis, Part 3: Chemical Methods*. Vol. 14 (John Wiley & Sons, 2020).
69. Weixin, C., Coleman, D. C., Carroll, C. R. & Hoffman, C. A. In situ measurement of root respiration and soluble C concentrations in the rhizosphere. *Soil Biol. Biochem.* **25**, 1189–1196 (1993).
70. Masto, R., Chhonkar, P., Purakayastha, T., Patra, A. & Singh, D. Soil quality indices for evaluation of long-term land use and soil management practices in semi-arid sub-tropical India. *Land Degradation Dev.* **19**, 516–529 (2008).
71. Andrews, S. S. & Carroll, C. R. Designing a soil quality assessment tool for sustainable agroecosystem management. *Ecol. Appl.* **11**, 1573–1585 (2001).
72. Andrews, S. S., Karlen, D. L. & Cambardella, C. A. The soil management assessment framework: a quantitative soil quality evaluation method. *Soil Sci. Soc. Am. J.* **68**, 1945–1962 (2004).
73. Li, K. et al. Evaluating the effects of agricultural inputs on the soil quality of smallholdings using improved indices. *Catena* **209**, 105838 (2022).
74. Bastida, F., Moreno, J. L., Hernández, T. & García, C. Microbiological degradation index of soils in a semiarid climate. *Soil Biol. Biochem.* **38**, 3463–3473 (2006).
75. Gee, G. W. & Or, D. 2.4 Particle-size analysis. *Methods Soil Analysis: Part 4 Phys. Methods* **5**, 255–293 (2002).
76. Dong, A., Chesters, G. & Simsiman, G. Soil dispersibility. *Soil Sci.* **136**, 208–212 (1983).
77. Bremner, J. M. Nitrogen-total. *Methods Soil Anal.: Part 3 Chem. Methods* **5**, 1085–1121 (1996).
78. Olsen, S., Sommers, L. & Page, A. Methods of soil analysis. *Part* **2**, 403–430 (1982).
79. Knudsen, D., Peterson, G. A., & Pratt, P. F. Lithium, sodium, and potassium. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*. **9**, 225–246 (1983).
80. Lindsay, W. L. & Norvell, W. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci. Soc. Am. J.* **42**, 421–428 (1978).
81. Alef, K. & Nannipieri, P. *Methods in Applied Soil Microbiology and Biochemistry* (Academic Press, 1995).
82. Bailey, V. L., Smith, J. L. & Bolton, H. Novel antibiotics as inhibitors for the selective respiratory inhibition method of measuring fungal: bacterial ratios in soil. *Biol. Fertil. Soils* **38**, 154–160 (2003).
83. Anderson, J. P. & Domsch, K. H. A physiological method for the quantitative measurement of microbial biomass in soils. *Soil Biol. Biochem.* **10**, 215–221 (1978).

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Author contributions

S.R and A.N. conceived the idea. M.B, F.A., and S.R. conducted the experiment and collected data. A.N., S.J., S.R., G.E., and R.Q. conducted the analysis. All authors including S.R., A.N., F.A., M.B., S.J., G.E., and R.Q. contributed equally to the interpretation of results and final draft of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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