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Impact of *Sesbania sesban* (L.) Merr. Cultivation on the Physicochemical Properties of Salt-Affected Soils

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ABSTRACT

Soil salinity is a major constraint to agricultural productivity and ecosystem sustainability in arid and semiarid regions, particularly in Iraq, where extensive areas are salt-affected. This study assessed *Sesbania sesban* (L.) Merr. as a biological reclamation crop for improving saline soil properties under field conditions in Tarmiyah District, north of Baghdad, using a 2×2 factorial design (saline and agricultural soils; vegetated and nonvegetated treatments) during the 2025 growing season. Results revealed that *S. sesban* markedly reduced soil salinity and sodicity, with electrical conductivity (EC) decreasing by 79.8% in saline soil and 77.0% in agricultural soil, Na^+ by 89.1% and 78.2%, Cl^- by 88.6% and 85.7%, and sodium adsorption ratio (SAR) by 77.6% and 58.9%, respectively, indicating efficient desalination and ion removal. In parallel, soil organic matter increased substantially by 296.7% and 325.4%, reflecting enhanced organic inputs and rhizosphere activity, while nitrogen declined by 31.8% and 74.1% due to net uptake under short-term cultivation. Phosphorus showed minor increases (2.0%–5.6%), whereas potassium exhibited contrasting trends, decreasing in saline soil (−4.9%) but increasing in agricultural soil (+29.2%), highlighting salinity-dependent nutrient dynamics. Soil pH and texture remained stable, confirming strong buffering capacity. Although salinity significantly suppressed plant performance—reducing stem length (−33.9%), root length (−24.3%), leaf number (−29.9%), and nodulation (−85.7%)—plants maintained functional growth and partial symbiotic activity, demonstrating notable salt tolerance. Overall, *S. sesban* operates as an integrated phytoremediation agent that simultaneously reduces salinity and enhances soil fertility through coupled physical, chemical, and biological mechanisms, supporting its application in sustainable reclamation of salt-affected soils.

1 | Introduction

Soil salinization is one of the most serious constraints to agricultural productivity and sustainability in arid and semiarid regions. It adversely affects plant growth, soil structure, and nutrient availability, ultimately leading to reduced crop yields and land degradation [1]. Globally, salt-affected soils occupy more than 1.4×10^9 ha, and this area continues to expand due to unsustainable irrigation practices, climate change, and poor drainage systems [2].

In Iraq, soil salinity represents a particularly severe and widespread environmental constraint, especially in central and southern regions where long-term irrigation, high evaporation rates, and inadequate drainage systems have accelerated salt accumulation. It is estimated that approximately 50%–70% of irrigated lands are affected by salinity to varying degrees, with a significant proportion already experiencing substantial productivity decline [2, 3]. This high level of salinity severity poses a major threat to soil functionality, agricultural sustainability, and national food security. Under these conditions, the

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development of efficient, low-cost, and environmentally sustainable reclamation strategies is urgently required.

To address soil salinity, several reclamation approaches have been developed, including physical, chemical, and biological methods. Physical approaches such as leaching, drainage installation, and irrigation management can rapidly reduce salt accumulation; however, their effectiveness is often limited by high freshwater demand and economic constraints [4]. Chemical amendments, including gypsum and organic materials, improve soil structure and ionic balance but require repeated application and may not be sustainable in the long term [5]. In contrast, biological approaches based on halophytic plants offer a more sustainable and ecologically sound alternative, particularly under water-limited environments [6].

Among biological reclamation strategies, salt-tolerant plants play an important role in soil reclamation through multiple mechanisms, including salt uptake, rhizosphere modification, improved soil structure, and stimulation of microbial activity. Halophytes tolerate salinity through a combination of physiological and biochemical mechanisms, including selective ion uptake, vacuolar sequestration of Na^+ and Cl^- to reduce cytotoxicity, maintenance of ionic balance through K^+ retention, and osmotic adjustment via compatible solutes such as proline and soluble sugars. In some species, salt levels are further regulated through exclusion at the root level or secretion via specialized salt glands. These adaptive strategies not only enable plant survival under saline conditions but also contribute to soil desalination and improved soil functionality over time [7]. Previous studies have demonstrated that halophytes such as *Tamarix* spp. and *Sesbania* species can significantly reduce soil electrical conductivity (EC) and improve physicochemical soil properties under saline conditions [8].

Sesbania sesban (L.) Merr. is a fast-growing leguminous species widely recognized for its high salt tolerance, nitrogen-fixing ability, and potential use as green manure [9, 10]. It can grow under moderately saline and alkaline conditions, where it contributes to soil improvement through biomass accumulation, biological nitrogen fixation, and organic matter (OM) input. Several studies have reported that *Sesbania* cultivation can reduce soil salinity, enhance soil fertility, and improve microbial activity, thereby increasing overall soil quality in degraded environments [1, 10, 11].

Although several studies have examined the role of *Sesbania* species in saline soil improvement, existing knowledge remains largely descriptive and often derived from crop rotation or amendment-based systems, where the specific contribution of *S. sesban* is not clearly isolated. Moreover, most studies report individual changes in salinity or nutrient parameters without addressing the mechanistic relationships linking these processes. In particular, the role of salinity reduction as a primary driver controlling subsequent ion redistribution and nutrient dynamics remains insufficiently understood, representing a critical knowledge gap. Therefore, this study aims to evaluate the independent effect of *S. sesban* under field conditions using a factorial design that separates vegetation and soil type effects, while also providing a mechanistic interpretation of soil reclamation processes. The novelty of this study lies in demonstrating that salinity reduction functions as a key regulatory process that triggers interconnected changes in soil ionic balance and fertility,

revealing a hierarchical pattern of soil recovery not previously clarified under field conditions.

2 | Materials and Methods

2.1 | Study Area and Experiment Design

The field experiment was conducted during the 2025 growing season at two adjacent sites in the Tarmiyah District, north of Baghdad, Iraq. The first site was characterized as saline soil ($33^{\circ}40'35''$ N, $44^{\circ}21'42''$ E), while the second site represented an agricultural soil ($33^{\circ}40'38''$ N, $44^{\circ}21'35''$ E). The proximity of the two sites ensured similar climatic conditions while allowing comparison between contrasting soil salinity levels.

The experiment was arranged in a completely randomized factorial design with two factors: soil type (saline and nonsaline) and vegetation (with and without *S. sesban* (L.) Merr.). This design resulted in four treatments: (i) saline soil without vegetation (control), (ii) saline soil planted with *S. sesban*, (iii) nonsaline soil without vegetation (control), and (iv) nonsaline soil planted with *S. sesban*. Each treatment was replicated five times.

Nonvegetated plots served as true controls for each soil type, allowing direct comparison with vegetated treatments and enabling the isolation of *S. sesban* effects from temporal variation in soil properties during the growing period. This factorial structure ensured that treatment effects were assessed based on vegetation presence rather than environmental fluctuations over time. Accordingly, treatment effects were evaluated based on factorial comparisons rather than pre- and postexperiment data alone.

Experimental plots measured 2×2 m (4 m^2) and were separated by 1 m buffer zones to minimize lateral movement of water and salt between plots. Standard agronomic practices were uniformly applied across all treatments, except for the imposed soil type and vegetation factors.

2.2 | Soil Sampling and Analysis

Before sowing, surface residues and gravel were removed from each plot. Composite soil samples (1 kg) were collected from the 0–30-cm soil depth prior to planting. Each composite sample was formed by combining 10 subsamples randomly collected from different locations within each plot using an auger. The subsamples were thoroughly mixed to obtain a representative sample of the plot. At the end of the experiment, soil sampling was repeated using the same procedure, sampling depth, and number of subsamples to ensure direct comparability between initial and final conditions. This standardized approach minimized spatial variability and sampling bias, thereby improving the reliability of temporal comparisons.

All collected soil samples were air-dried at room temperature, gently crushed, homogenized, and passed through a 2-mm sieve to obtain fine soil materials suitable for laboratory analyses.

Baseline soil properties assessed prior to planting included soil texture, pH, EC, soluble cations (Na^+ , Ca^{+2} , and Mg^{+2}), anions (HCO_3^- , SO_4^{2-} , and Cl^-), sodium adsorption ratio (SAR), OM content, and available nitrogen (N), phosphorus (P), and potassium (K). The same set of parameters was reanalyzed at the end of the experimental period under identical analytical

procedures, with preplanting measurements serving as baseline reference values for evaluating treatment-induced changes.

Soil physicochemical analyses were conducted following standard laboratory methods. Soil texture was analyzed using the hydrometer method as described by Gee and Bauder [12]. Soil pH and EC were determined in a 1:1 soil–water suspension, a digital pH meter (S400), and an EC meter (BEPM510), respectively [13]. Soluble cations (Na^+ , Ca^{2+} , and Mg^{2+}) and anions (Cl^- , SO_4^{2-} , and HCO_3^-) were quantified from soil extracts using standard titration procedures. SAR was calculated based on the concentrations of Na^+ , Ca^{2+} , and Mg^{2+} .

Soil OM was measured using the Walkley–Black dichromate oxidation method [14], while available nitrogen (N) was determined by the Kjeldahl method, available phosphorus (P) by the Olsen method, and available potassium (K) using flame photometry [15]. All analyses followed standard protocols outlined by FAO and USDA.

2.3 | Planting and Crop Management

Seeds of *S. sesban* were sown manually at a uniform depth of 1 cm and using a consistent seeding rate. After sowing, the seeds were lightly covered with soil and irrigated to field capacity. Irrigation was subsequently applied every 2–3 days throughout the experimental period to maintain adequate soil moisture under non–water-limiting conditions. Equal volumes of water were applied to all plots to ensure uniform moisture conditions. Equal volumes of irrigation water were applied to all plots to ensure uniform moisture distribution.

Irrigation water samples were collected from the Tigris river for physicochemical analysis, and their properties are presented in Table 1.

2.4 | Vegetative Growth and Morphological Characteristics

At full vegetative maturity, five randomly selected plants per plot were evaluated for the stem height (cm), number of branches per plant, number of leaves per plant, root length (cm), and number of root nodules per plant.

2.5 | Statistical Analysis

Prior to statistical analysis, all soil and plant growth data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene’s test. All data met the assumptions of normality and homoscedasticity; therefore, parametric statistical analyses were applied. Subsequently, data were subjected to two-way analysis of variance (ANOVA) using IBM SPSS Statistics Version 28 to evaluate the main effect of soil type, *S. sesban* plantation, and their interaction. Soil properties measured before planting were used as baseline reference values, while statistical analysis was performed on postharvest data. Mean comparisons among treatments were conducted using Tukey’s honestly significant difference (HSD) test at $p \leq 0.05$.

3 | Results and Discussion

The experimental design incorporated both vegetated and nonvegetated treatments within each soil type, allowing for a direct evaluation of *S. sesban* effects relative to unplanted

controls. The inclusion of parallel control plots ensured a clear distinction between vegetation-induced changes and natural temporal variability, as the physicochemical properties of unplanted soils remained stable between sampling periods. Furthermore, the 2×2 factorial arrangement (soil type $\times$ vegetation) strengthened the analytical framework by enabling assessment of interaction effects, thereby supporting a more robust and mechanistic interpretation of treatment responses.

The physicochemical properties of saline and agricultural soils under vegetated (*S. sesban* cultivated) and unplanted conditions are presented in Tables 2 and 3, with relative percentage changes illustrated in Figure 1. Overall, the results indicate that *S. sesban* cultivation induced substantial modifications in soil properties, reflecting integrated biological, physical, and chemical processes driven by plant–soil interactions rather than isolated changes in individual parameters.

3.1 | Salinity and Sodicity Reduction as the Primary Driver

The cultivation of *S. sesban* produced pronounced improvements in soil salinity and sodicity parameters across both soil types. In saline soil, EC decreased markedly from 44 to 8.90 dS/m (–79.8%), while Na^+ declined from 446.90 to 48.80 meq/L (–89.1%), Cl^- from 237 to 27 meq/L (–88.6%), and SAR from 51.90 to 11.61 (–77.6%) (Table 2; Figure 1). Comparable trends were observed in agricultural soil, where EC reduced from 35.2 to 8.10 dS/m (–77.0%), Na^+ from 123 to 26.84 meq/L (–78.2%), Cl^- from 332 to 47.50 meq/L (–85.7%), and SAR from 12.30 to 5.05 (–58.9%) (Table 3; Figure 1).

The consistent reductions observed across all salinity-related parameters indicate a coordinated desalination process rather than isolated changes in individual ions. These changes are primarily attributed to plant–soil interactions, with limited influence from irrigation water quality. Given that the irrigation water remained within FAO-recommended limits for most parameters (Table 1), it did not constitute a significant source of salinity input, and its contribution to the observed declines in soil EC, and SAR is considered negligible.

The extensive root system of *S. sesban* enhanced soil structure through aggregation and increased macroporosity, which facilitated downward leaching of soluble salts beyond the rhizosphere. Concurrently, direct uptake of Na^+ and Cl^- by plant tissues contributed to the reduction of soluble salt pools, while the associated decline in Na^+ availability directly reduced SAR, reflecting partial alleviation of sodicity stress.

Importantly, this initial reduction in salinity acted as a triggering mechanism, creating more favorable conditions for subsequent changes in ion distribution, nutrient dynamics, and biological activity. These findings are consistent with Lu et al. [11] and Wu et al. [1], who reported similar reductions in salinity parameters under salt-tolerant legumes. However, the magnitude of change observed in the present study is substantially higher, which may be attributed to differences in initial salinity levels, field conditions, and the isolation of vegetation effects through the factorial design. This suggests that soil responses under *S. sesban* cultivation are strongly context-dependent rather than uniform across systems. In contrast, Zaid et al. [17] emphasized that while EC and soluble salts may respond rapidly to vegetation

TABLE 1 | Physicochemical properties of irrigation water collected from the Tigris river.

Water property	Unit	Measured value	Reference values (FAO)*
pH	—	7.50	6.5–8.5
Electrical conductivity (EC)	dS/m	0.97	< 0.7 (low salinity) 0.7–3.0 (moderate)
Calcium (Ca ²⁺)	meq/L	5	0–20
Magnesium (Mg ²⁺)	meq/L	5	0–5
Sodium (Na ⁺)	meq/L	2.96	< 9
Bicarbonate (HCO ₃ ⁻)	meq/L	7.5	< 1.5 (low) 1.5–8.5 (moderate)
Chloride (Cl ⁻)	meq/L	2.5	< 4
Sulfate (SO ₄ ²⁻)	meq/L	6.06	< 20
Sodium adsorption ratio (SAR)	—	0.69	< 10 (low hazard)

*Reference values according to FAO guidelines [16].

establishment, full recovery of sodicity indicators such as SAR often requires longer-term intervention, highlighting the temporal dynamics of biological soil reclamation.

3.2 | Ion Redistribution as a Secondary Response to Desalination

Following salinity reduction, clear shifts in soil ionic composition were observed. Divalent cations (Ca²⁺ and Mg²⁺) decreased substantially in agricultural soil (Ca²⁺: 150 to 20 meq/L [−86.7%]; Mg²⁺: 130 to 52.50 meq/L [−59.6%]) but showed more moderate reductions in saline soil (Ca²⁺: 32.50 to 27.50 meq/L [−15.4%]; Mg²⁺: 40 to 22.50 meq/L [−43.8%]). These patterns reflect the influence of initial soil conditions and indicate redistribution rather than depletion, driven by enhanced leaching, exchange reactions, and plant uptake. Similar trends have been reported by Zheng et al. [18] and Wu et al. [1], who highlighted that legume-based reclamation often leads to redistribution of divalent cations within the soil profile alongside improvements in soil physical conditions rather than uniform depletion.

However, Mustafa et al. [19] highlighted that the stabilization of exchangeable Ca²⁺ and Mg²⁺ fractions requires longer-term cultivation, as short-term variations likely reflect transitional adjustments toward a new soil chemical equilibrium.

In parallel, anionic behavior further supports this redistribution process, exhibiting distinct patterns across treatments. Chloride exhibited the greatest decline in both soils (> 85%), reflecting its high solubility and strong susceptibility to leaching under improved hydraulic conditions. Bicarbonate (HCO₃⁻) also decreased, from 6.0 to 3.50 meq/L (−41.7%) in saline soil and from 6.50 to 3.50 meq/L (−46.2%) in agricultural soil, indicating partial alleviation of alkalinity through rhizosphere processes such as CO₂ release and carbonic acid formation that enhance bicarbonate transformation and removal. In contrast, sulfate (SO₄²⁻) showed divergent behavior, decreasing in saline soil from 63.08 to 48.92 meq/L (−22.5%) but increasing in agricultural soil from 24.07 to 30.31 meq/L (+26.0%), reflecting its lower mobility and association with mineral phases such as calcium sulfate. These findings are consistent with those of Srivastava [20] and

TABLE 2 | Physicochemical characteristics of saline soil before (unplanted) and after *Sesbania sesban* plantation.

Soil property	Unit	Saline soil		Change (%)
		Control (unplanted soil)	After <i>Sesbania sesban</i> plantation	
pH	—	7.40 ± 0.07 a	7.50 ± 0.11 a	No significant change
Electrical conductivity (EC)	dS/m	44 ± 0.74 a	8.90 ± 0.09 b	−79.8
Calcium (Ca ²⁺)	meq/L	32.50 ± 0.7 c	27.50 ± 1.03 d	−15.4
Magnesium (Mg ²⁺)	meq/L	40 ± 1.53 b	22.50 ± 1.62 c	−43.8
Sodium (Na ⁺)	meq/L	446.90 ± 4.71 a	48.80 ± 1.14 b	−89.1
Bicarbonate (HCO ₃ ⁻)	meq/L	6.0 ± 0.5 a	3.50 ± 0.35 b	−41.7
Chloride (Cl ⁻)	meq/L	237 ± 1.25 b	27 ± 1.10 c	−88.6
Sulfate (SO ₄ ²⁻)	meq/L	63.08 ± 0.5 a	48.92 ± 0.003 b	−22.5
Nitrogen (N)	mg/kg	154 ± 0.81 b	105 ± 0.32 c	−31.8
Phosphorus (P)	mg/kg	30.91 ± 0.19 a	31.52 ± 0.22 a	+2.0
Potassium (K)	mg/kg	122 ± 1.34 b	116 ± 0.87 b	−4.9
Organic matter (OM)	g/kg	0.60 ± 0.07 c	2.38 ± 0.02 b	+296.7
Sodium adsorption ratio (SAR)	—	51.90 ± 0.46 a	11.61 ± 0.14 b	−77.6
Soil texture	—	Loamy clay a	Loamy clay a	No significant change

Note: Values are presented as mean ± standard error (SE) of five replicates (*n* = 5). Means within the same row followed by the same lowercase letter are not significantly different, whereas means with different lowercase letters (a, b, c, d) indicate significant differences according to Tukey's HSD multiple comparison test at *p* ≤ 0.05.

TABLE 3 | Physicochemical characteristics of agricultural soil before (unplanted) and after *Sesbania sesban* plantation.

Soil property	Unit	Agricultural soil		Change (%)
		Control (unplanted soil)	After <i>Sesbania sesban</i> plantation	
pH	—	7.20 ± 0.08 a	7.20 ± 0.06 a	No significant change
Electrical conductivity (EC)	dS/m	35.2 ± 0.9 a	8.10 ± 0.24 b	−77.0
Calcium (Ca ²⁺)	meq/L	150 ± 11.67 a	20 ± 1.07 b	−86.7
Magnesium (Mg ²⁺)	meq/L	130 ± 1.91 a	52.50 ± 0.83 b	−59.6
Sodium (Na ⁺)	meq/L	123 ± 0.5 c	26.84 ± 0.5 d	−78.2
Bicarbonate (HCO ₃ [−])	meq/L	6.50 ± 0.12 a	3.50 ± 0.11 b	−46.2
Chloride (Cl [−])	meq/L	332 ± 3.5 a	47.50 ± 0.96 d	−85.7
Sulfate (SO ₄ ^{2−})	meq/L	24.07 ± 0.59 c	30.31 ± 0.22 b	+26.0
Nitrogen (N)	mg/kg	189 ± 0.6 a	49 ± 0.74 d	−74.1
Phosphorus (P)	mg/kg	15.15 ± 0.39 b	16 ± 0.5 b	+5.6
Potassium (K)	mg/kg	96 ± 1.07 c	124 ± 0.87 a	+29.2
Organic matter (OM)	g/kg	0.67 ± 0.02 c	2.85 ± 0.03 a	+325.4
Sodium adsorption ratio (SAR)	—	12.30 ± 0.14 c	5.05 ± 0.006 d	−58.9
Soil texture	—	Loamy clay a	Loamy clay a	No significant change

Note: Values are presented as mean ± standard error (SE) of five replicates (*n* = 5). Means within the same row followed by the same lowercase letter are not significantly different, whereas means with different lowercase letters (a, b, c, d) indicate significant differences according to Tukey’s HSD multiple comparison test at *p* ≤ 0.05.

Peng et al. [21], who reported that chloride-dominated salinity is more readily alleviated through leaching processes, whereas sulfate salts tend to be more stable and may persist or even

accumulate depending on soil composition and hydrological conditions. However, Mustafa et al. [19] and Slatni et al. [22] suggested that sulfate dynamics may become more responsive

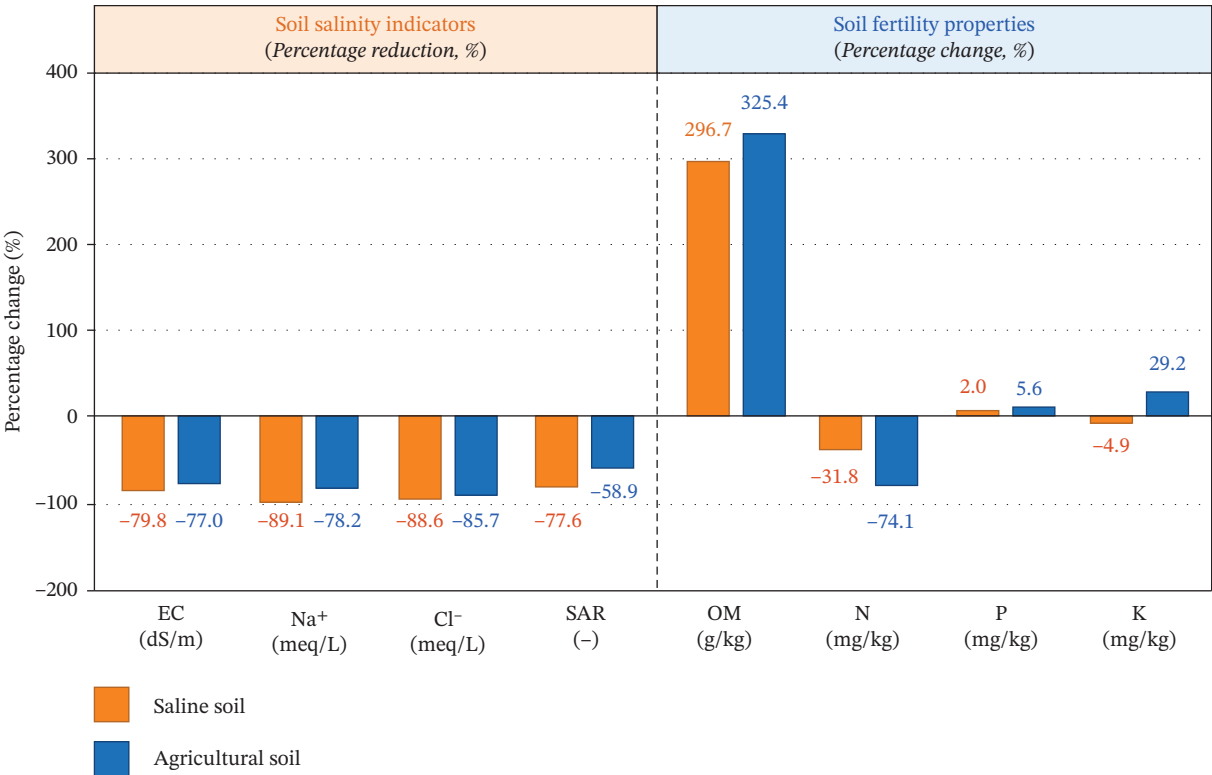


FIGURE 1 | Percentage change (%) in soil physicochemical properties after *S. sesban* cultivation in saline and agricultural soils. Negative values indicate reductions, while positive values indicate increases relative to baseline (unplanted) conditions. Salinity-related parameters (EC, Na⁺, Cl[−], and SAR) showed substantial decreases in both soils, with greater reductions observed in saline soil. In contrast, soil fertility indicators exhibited variable responses, including marked increases in organic matter (OM) and moderate changes in nutrient availability (N, P, and K), reflecting the combined effects of plant uptake, improved soil structure, and rhizosphere-driven processes.

over longer time scales as soil structure and calcium-mediated processes continue to evolve, indicating that short-term observations may not fully capture long-term equilibrium shifts in anion distribution.

Together, these results demonstrate that ion dynamics are governed by solubility, exchange processes, and structural improvements induced by salinity reduction, confirming that phytoremediation by *S. sesban* not only reduces salinity and sodicity but also drives the internal redistribution of soil ions through integrated plant–soil mechanisms.

3.3 | Soil Fertility and OM Dynamics

Changes in soil fertility parameters were more variable but closely linked to the preceding improvements in salinity and ion balance. OM increased markedly in both soils, rising from 0.60 to 2.38 g/kg (+296.7%) in saline soil and from 0.67 to 2.85 g/kg (+325.4%) in agricultural soil, reflecting enhanced carbon inputs from plant biomass and root residues, together with intensified rhizosphere activity that stimulates microbial processes and accelerates OM turnover. The increase is further linked to concurrent reductions in EC, SAR, and exchangeable Na^+ , which alleviate salinity stress and create more favorable conditions for microbial activity and carbon stabilization. Improved soil structure and aggregation also contribute to the protection and accumulation of OM through organomineral interactions. These findings are consistent with previous studies [23–25] reporting enhanced OM under legume-based reclamation, although longer time scales may be required for stabilization of more recalcitrant carbon fractions. However, Lehmann and Kleber [26] reported that short-term increases in OM may primarily reflect the accumulation of labile carbon fractions rather than stable organic pools, and that environmental constraints such as salinity and limited microbial activity may restrict long-term carbon stabilization.

Despite this increase in OM, total nitrogen declined from 154 to 105 mg/kg (−31.8%) in saline soil and from 189 to 49 mg/kg (−74.1%) in agricultural soil. This reduction indicates that nitrogen removal through plant uptake exceeded replenishment during the cultivation period. The decline can be attributed to the combined effects of increased plant demand under improved growth conditions and constrained nitrogen inputs, particularly under saline stress, where elevated salinity is known to suppress rhizobial activity and reduce the efficiency of biological nitrogen fixation. Nevertheless, the persistence of nodulation suggests that partial symbiotic activity was maintained, contributing to some level of nitrogen input and mitigating more severe depletion. These results therefore reflect a dynamic balance between nitrogen consumption and biologically mediated replenishment. The findings are consistent with previous studies [1, 9, 27], which reported that legume-based systems under saline conditions may sustain partial nitrogen fixation but often exhibit net nitrogen declines in the short term due to stress-induced constraints on microbial processes. However, Ashraf et al. [28] and Slatni et al. [22] suggest that longer-term cultivation can gradually enhance nitrogen status as soil conditions improve and symbiotic efficiency recovers, indicating that the observed decrease may represent a transitional phase rather than a stable nitrogen equilibrium.

Available phosphorus (P) exhibited slight increases in both soils, rising from 30.91 to 31.52 mg/kg in saline soil (+2.0%) and from

15.15 to 16.00 mg/kg in agricultural soil (+5.6%) (Tables 2 and 3), indicating a limited short-term response of P availability to biological reclamation. This limited response reflects the strongly buffered nature of phosphorus cycling, where availability is primarily controlled by sorption–desorption equilibria and precipitation reactions with Ca, Fe, and Al compounds, particularly in alkaline and saline systems where P is stabilized in low-solubility forms. From a mechanistic perspective, the minor increase in available P may reflect localized rhizosphere effects, including organic acid exudation and enhanced microbial activity that promote partial dissolution of mineral-bound phosphates; however, these processes appear insufficient within the short experimental period to induce a substantial shift in the overall soil P pool. In contrast, potassium (K) exhibited a contrasting response, decreasing slightly in saline soil (122 to 116 mg/kg; −4.9%) but increasing significantly in agricultural soil (96 to 124 mg/kg; +29.2%) (Tables 2 and 3). This divergence reflects the strong influence of salinity on cation dynamics, where high Na^+ levels promote competitive displacement of K^+ from exchange sites and increase its susceptibility to leaching, while also limiting root uptake under osmotic stress. Conversely, reductions in EC, Na^+ , and SAR improved cation exchange conditions, soil structure, and root activity, thereby enhancing K retention and availability. This effect was further supported by increased OM, which promotes aggregation and stabilizes exchange sites. Overall, these contrasting patterns emphasize that phosphorus remains largely kinetically constrained in the short term, whereas potassium is highly dynamic and strongly regulated by salinity-driven cation competition and improvements in soil physicochemical conditions, in agreement with Lu et al. [11], who emphasized the dominant role of ionic competition and soil structural changes in controlling K availability under reclamation systems. However, some discrepancies exist regarding the magnitude of nutrient changes, particularly for P and K, which may be attributed to differences in experimental duration, initial soil salinity levels, and soil buffering capacity, suggesting that nutrient responses under phytoremediation systems are highly context-dependent rather than uniform across studies.

Overall, these patterns indicate that nutrient dynamics are not independent responses but are tightly coupled with salinity reduction and ion redistribution processes, collectively driven by improvements in soil structure and plant–soil interactions.

3.4 | Soil pH and Structural Stability

In contrast to the pronounced changes observed in salinity and ion dynamics, soil pH remained relatively stable during the cultivation period, with a slight increase in saline soil from 7.40 to 7.50, while it remained unchanged in agricultural soil at 7.20. This stability reflects the strong buffering capacity of soils, primarily regulated by carbonate–bicarbonate equilibria, clay minerals, and exchangeable cations. Although *Sesbania*, as a leguminous plant, can influence rhizosphere processes through nitrogen fixation, proton release, and organic acid exudation, these effects are often localized and insufficient to alter bulk soil pH, especially in buffered saline systems. The slight increase in pH in saline soil may be attributed to shifts in carbonate–bicarbonate equilibria following improved leaching and salt removal, together with changes in soil solution chemistry induced by root activity. Similar observations were reported by Zheng et al. [18] and Wang and Kuzyakov [29], who

demonstrated that biological reclamation strategies primarily influence salinity-related parameters rather than soil pH over short periods. However, some studies have reported gradual pH reductions under long-term phytoremediation due to sustained OM inputs and enhanced microbial activity [22, 28], indicating that soil pH response is strongly time-dependent and becomes more evident over extended periods.

Similarly, soil texture remained unchanged across all treatments (loamy clay), confirming that short-term cultivation with *S. sesban* does not alter the inherent particle-size distribution of the soil, which is primarily controlled by parent material and long-term pedogenic processes. This is consistent with previous studies indicating that texture is a relatively stable soil property that is not significantly affected by short-term biological or agronomic interventions [30]. Accordingly, the findings suggest that biological reclamation primarily targets soil chemical properties rather than inducing rapid changes in fundamental physical composition. In contrast, the marked increase in soil OM observed in this study indicates a clear potential for progressive improvements in soil physical functioning. Increased organic inputs from plant residues and root biomass, together with enhanced microbial activity, promote the formation of stable soil aggregates through binding agents such as polysaccharides and humic substances. This process improves soil aggregation, porosity, and structural stability without altering the primary particle-size distribution. These structural improvements are functionally linked to the observed reductions in salinity, as enhanced aggregation and porosity facilitate water movement and salt leaching, reinforcing the coupled processes of soil chemical and physical recovery. Therefore, although texture remained constant, structural quality is expected to improve gradually with continued cultivation, leading to enhanced water infiltration, aeration, and reduced susceptibility to compaction over time. These observations align with Pirasteh-Anosheh et al. [7], who reported that OM accumulation enhances soil aggregation and structural stability, while fundamental texture remains largely unchanged except over long pedogenic timescales.

3.5 | Plant Growth (Vegetative and Morphological Response)

Vegetative growth and morphological traits of *S. sesban* were significantly affected ($p \leq 0.05$) by soil type, as clearly illustrated in Figure 2. Plants grown in agricultural soil consistently showed superior performance across all measured traits compared with those grown in saline soil. Stem length increased markedly from 41.70 cm in saline soil to 63.10 cm in agricultural soil, reflecting a substantial reduction of approximately 33.9% under salinity stress. Similarly, root length increased from 10.30 cm to 13.60 cm, indicating a 24.3% decrease in saline conditions, which highlights the strong sensitivity of root development to soil salinity. The superior performance of plants in agricultural soil compared with saline soil reflects the strong impact of salinity on plant growth. The reductions in stem length (−33.9%) and root length (−24.3%) under saline conditions can be attributed to elevated EC and SAR, which induce osmotic stress and ionic imbalance [31]. Reduced soil water potential limits water uptake and decreases cell turgor, thereby inhibiting cell elongation in both shoots and roots. At the same time, excessive Na^+ interferes with the uptake of essential nutrients such as K^+ and Ca^{2+} , impairing root meristem activity and overall plant metabolism [32]. Since

root systems are directly exposed to soil stress, their inhibition further restricts water and nutrient acquisition, which in turn amplifies the reduction in shoot growth.

Leaf production also showed a clear response to soil type, increasing from 18.80 leaves per plant in saline soil to 26.80 leaves per plant in agricultural soil, representing a 29.9% reduction under salinity stress. This decline is likely associated with reduced photosynthetic efficiency, as osmotic stress induces stomatal closure and limits CO_2 assimilation, while ionic toxicity accelerates leaf senescence, thereby restricting leaf formation. In contrast, branch number showed only a slight variation, ranging from 15.20 in saline soil to 16.60 in agricultural soil, corresponding to a minor decrease of 8.4%, indicating relatively low sensitivity to salinity. This suggests that branching is less directly influenced by short-term physiological stress and may be more controlled by developmental regulation, allowing it to remain comparatively stable under saline conditions [31].

The most pronounced effect of salinity was observed in root nodulation, where the number of nodules dramatically decreased from 15.40 nodules per plant in agricultural soil to only 2.20 nodules per plant in saline soil, representing an extreme reduction of 85.7%. This substantial decrease is directly linked to high EC and SAR in saline soil, which negatively affects rhizobial survival, root infection processes, and nodule formation. In addition, salinity inhibits nitrogenase activity within nodules, leading to a significant reduction in biological nitrogen fixation.

Although soil pH remained relatively stable, its interaction with salinity likely influenced nutrient availability, particularly phosphorus and micronutrients, thereby contributing indirectly to the observed differences in plant growth and nodulation. Overall, these results indicate that reductions in plant growth and symbiotic activity were governed by the interactive effects of salinity (EC), sodicity (SAR), and nutrient imbalance. While most vegetative traits were negatively affected, root nodulation emerged as the most sensitive indicator of stress, whereas branching exhibited relatively greater tolerance.

Despite these limitations, the ability of *S. sesban* to maintain measurable growth and some level of nodulation in saline soil highlights its inherent tolerance and adaptive capacity, likely mediated by physiological mechanisms such as ion compartmentalization, osmotic adjustment, and selective nutrient uptake. This resilience is particularly important in phytoremediation contexts, as sustained biomass production and partial symbiotic activity are essential for continuous OM input and gradual soil improvement under stress conditions. These findings are consistent with Sarwar et al. [9] and Wu et al.'s study [1], who reported reduced but persistent growth and nodulation of salt-tolerant legumes under salinity stress, emphasizing that although salinity significantly limits plant performance, complete functional inhibition does not occur in tolerant species such as *S. sesban*.

3.6 | Conceptual Model of Soil Reclamation by *S. sesban*

The results of this study support a conceptual model in which *S. sesban* functions as a biological driver of integrated soil reclamation through tightly interconnected physical, chemical, and biological processes. Initially, root development enhances soil

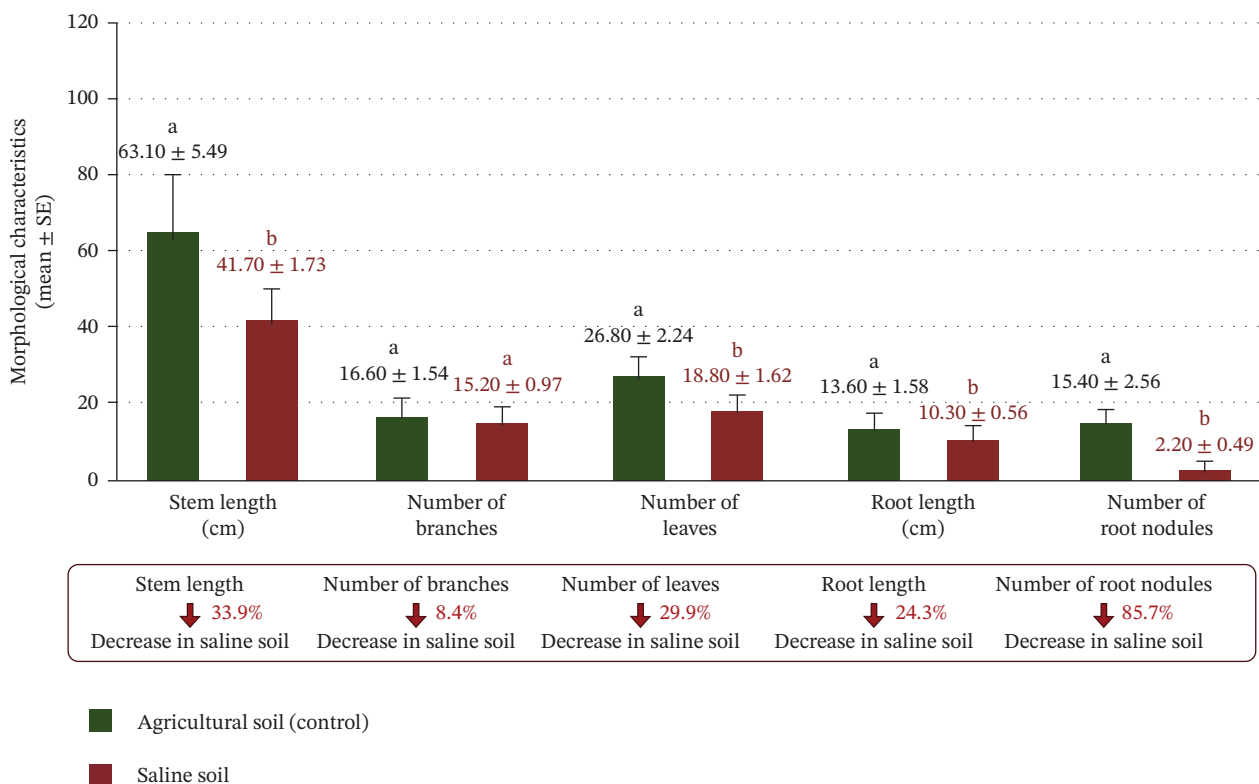


FIGURE 2 | Vegetative growth and morphological responses of *S. sesban* under agricultural and saline soil conditions. The figure shows the effects of soil type on vegetative growth and morphological traits of *S. sesban*. Plants grown in agricultural soil exhibited higher growth performance, including greater stem and root length, leaf production, and overall vigor compared to those grown in saline soil. Salinity stress resulted in a clear reduction in all measured parameters. The figure also presents the percentage reduction in the studied traits between the two soil types, highlighting the magnitude of salinity-induced growth inhibition.

structure by increasing aggregation and macroporosity, which improves water infiltration and facilitates the leaching of soluble salts (Na^+ and Cl^-). This leads to reductions in EC and SAR, thereby alleviating osmotic stress and ionic toxicity and creating more favorable conditions for root growth and microbial activity.

Simultaneously, root activity and rhizosphere processes stimulate ion redistribution through cation exchange and dissolution-precipitation reactions, resulting in the reorganization of Ca^{2+} , Mg^{2+} , and SO_4^{2-} within the soil profile. These changes are further reinforced by increasing OM inputs derived from plant biomass and root exudates, which enhance soil aggregation, cation exchange capacity, and microbial activity.

As soil conditions progressively improve, nutrient dynamics respond accordingly. Potassium availability increases due to reduced competition with Na^+ , while nitrogen dynamics reflect a transitional balance between plant uptake and limited biological nitrogen fixation under residual salinity stress. Although pH changes remain minimal in the short term due to soil buffering capacity, localized rhizosphere activity contributes to gradual chemical adjustments.

Overall, these interacting processes operate as a positive feedback system in which improvements in soil structure and salinity further enhance plant growth, thereby accelerating soil recovery through continuous organic inputs and root-mediated processes. This conceptual framework highlights that phytoremediation by *S. sesban* is not governed by a single mechanism but rather by a coupled soil-plant system driving progressive restoration of soil

functionality. The integrated interactions among physical, chemical, and biological processes are summarized in the conceptual model presented in Figure 3.

3.7 | Limitations of the Study

While the present study provides meaningful insights into the role of *S. sesban* in soil reclamation, several methodological limitations should be considered when interpreting the findings within a broader temporal and field-scale context.

First, the experimental duration was relatively short, which may not adequately capture the long-term trajectory of soil restoration processes. Soil reclamation under saline conditions is inherently slow and governed by cumulative biophysical and biogeochemical feedbacks that often require extended timeframes to stabilize. Consequently, some of the observed improvements may represent early-stage responses rather than fully developed equilibrium conditions.

Second, the study design did not incorporate high-resolution temporal monitoring across multiple growth cycles or seasonal phases. This limits the ability to resolve dynamic shifts in soil-plant-microbial interactions, particularly those associated with progressive salinity attenuation, nutrient cycling, and rhizosphere restructuring over time.

Third, although experimental conditions were controlled to reduce external variability, complete environmental standardization was not achievable. Residual heterogeneity in soil

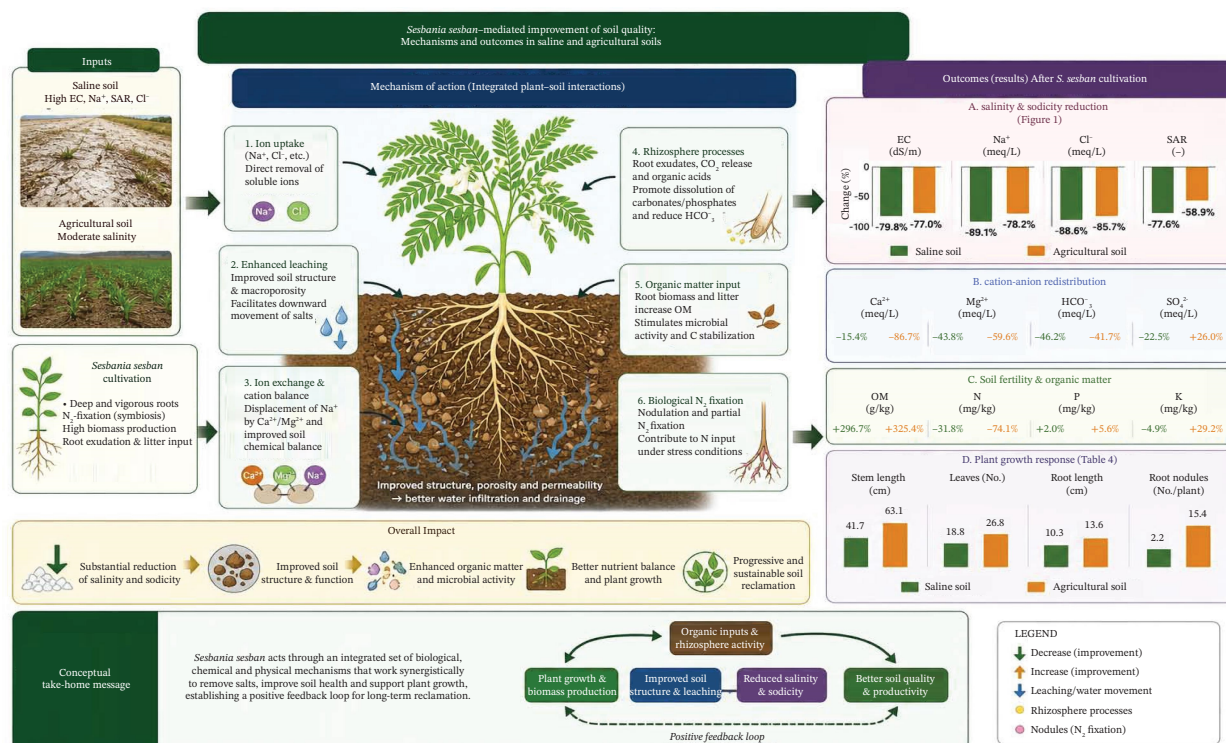


FIGURE 3 | Conceptual model of soil reclamation mechanisms driven by *S. sesban*. The model shows the integrated physical, chemical, and biological processes involved in soil reclamation. Root development improves soil structure and enhances salt leaching, leading to reduced EC and SAR. Rhizosphere activity promotes ion redistribution and organic matter accumulation, improving soil fertility and microbial function. These interactions form a positive feedback system that progressively enhances plant growth and accelerates soil restoration.

microstructure and microclimatic factors may have introduced variability in treatment responses, particularly in parameters sensitive to localized rhizosphere effects.

Collectively, these limitations suggest that the results should be interpreted as representative of short-term functional trends rather than long-term stabilization outcomes. Accordingly, extrapolation to field-scale reclamation systems should be undertaken with caution, particularly in heterogeneous or climatically variable environments.

Future research should therefore prioritize long-term, multi-seasonal field investigations combined with continuous monitoring of soil physicochemical and biological indicators to better resolve the temporal evolution of *S. sesban*-mediated reclamation processes.

4 | Conclusions

This study confirms that *S. sesban* (L.) Merr. is a highly effective biological agent for the reclamation of salt-affected soils under field conditions. Its cultivation induced significant improvements in key soil chemical properties, demonstrating a consistent reduction in salinity and sodicity and indicating an active role in salt mitigation and ion redistribution within the soil system. Concurrently, soil fertility was enhanced through increased OM and moderated nutrient dynamics, reflecting the combined influence of plant-soil interactions, rhizosphere activity, and improved soil conditions. In contrast, soil pH and texture remained stable, suggesting that biological reclamation primarily targets soil chemical processes in the short term without altering

inherent physical properties. Although plant growth and nodulation were reduced under saline conditions, *S. sesban* maintained functional development and symbiotic activity, highlighting its resilience and suitability for harsh environments. Overall, the findings demonstrate that *S. sesban* operates as an integrated phytoremediation system capable of initiating and sustaining soil quality improvement, supporting its application as a sustainable strategy for the rehabilitation of saline soils in arid regions. However, long-term implementation is necessary to ensure the stabilization and full development of soil recovery processes.

Author Contributions

Maryam Waleed Khaleel conducted the field experiment, performed data collection and laboratory analyses, and drafted the initial version of the manuscript as part of her Master's thesis. Zeena Ghazi Faisal supervised the research, contributed to the study design and data interpretation, and critically revised the manuscript for important intellectual content. The corresponding author (Zeena Ghazi Faisal) had full access to all of the data in this study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

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Disclosure

Both authors read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

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