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Research Article

A GIS-based Approach to Assessing the Spatial Variability and Rhizosphere Soil Properties of *Retama raetam* Forssk., Growing in Southern Algeria

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ABSTRACT

Fabaceae shrubs like *Retama raetam* L. can reshape soil chemistry through rhizosphere-microbe interactions, yet their spatial effects in arid lands remain underexplored. The main objective of the study is to assess and quantify the interactions of rhizosphere soil associated with *Retama raetam* and its spatial variability in the Sebseb region, Algeria. Rhizosphere (RS) and bulk soil (BS) were sampled and analyzed for pH, electrical conductivity (EC), organic matter (OM), $CaCO_3$, available phosphorus (AP), mineral nitrogen (NO_3), total nitrogen (TN), and soluble/total sodium and potassium (SNa/TNa, SK/TK). RS-BS contrasts, correlations, and spatial structure were assessed using variograms and ordinary kriging. RS/BS comparison revealed significant differences in several characteristics. EC ($p < 0.0001$), $CaCO_3$ ($p < 0.0001$), and TN ($p = 0.0069$) were higher in BS. RS exhibited a significantly lower pH ($p < 0.0001$), while NO3 ($p = 0.01$) and TK ($p = 0.01$) levels were higher. All variables fit Gaussian variograms, except EC, pH, SNa, and TNa, which were better fitted in spherical models; nugget: sill <25% indicated strong spatial dependence. Kriging maps revealed nutrient hotspots (EC, NO_3, AP) and broader pedogenic patterns ($CaCO_3$, pH) across Sebseb soils. Rhizosphere soil had lower pH and higher NO3, while bulk soil harbored more $CaCO_3$, EC, and TN, highlighting distinct biological and pedogenic processes. Geostatistical analysis indicated strong spatial dependence, with short-range variability linked to rhizosphere effects and longer ranges driven by environmental factors. Overall, *Retama raetam* enhances nutrient availability and soil fertility, supporting its role in sustainable land management.

Keywords: Rhizosphere soil, GIS, kriging, spatial variability, arid ecosystems.

Introduction

Soil is considered a crucial area of scientific inquiry, with the rhizosphere being its most active part. its active microbial community and its interactions with plant roots make it a target for biotechnological applications aimed at

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improving crop yields and soil health [1, 2]. Understanding these processes better is essential for preserving the plant cover in arid and semi-arid regions. The rhizosphere, commonly referred to as the "microbial reservoir," is home to diverse microorganisms and other organisms that engage in complex interactions at the root interface [3, 4], which in turn exert a significant influence on the soil's biological and chemical characteristics [5].

Soil fertility and its management are central to sustainable agriculture, particularly in arid and semi-arid ecosystems where water scarcity and poor soil quality limit crop productivity [6, 7]. Leguminous plants play a key role in enhancing soil fertility through organic matter input and symbiotic nitrogen fixation, thereby supporting agricultural sustainability in fragile environments [8]. They improve soil structure and reduce erosion. This is particularly beneficial in marginal lands where soil fertility is low [9]. Among these, *Retama raetam*, commonly known as Rtem, is a leguminous shrub native to North Africa, Eastern Mediterranean, and Middle East countries, it is widely used in folk medicine, as a powder, an infusion, or a decoction, to treat different diseases such as diabetes [10]. It is also recognized to exhibit antimicrobial activity [11, 12]. This plant has garnered attention for its specialized metabolites, which have potential applications in biopesticides and sustainable agriculture [13].

The *R. raetam* plant, due to its remarkable germinative ability, its capacity to endure water stress, and its unique root branching pattern, is recommended for use in vegetation restoration in fragile environments. Thanks to their strong symbiotic capacity, Retama species, particularly through their associations with nitrogen-fixing rhizobacteria, play a crucial role in biofertilizing saline and nutrient-poor soils, significantly contributing to the nitrogen cycle. These interactions enhance soil fertility and promote sustainable agricultural practices by converting atmospheric nitrogen into mineral nitrogen [14, 8].

Spatial variability of soil parameters represents one of the most fundamental aspects of modern agricultural science and environmental management. Understanding how soil properties vary across landscapes is essential for implementing effective precision agriculture strategies, optimizing resource use, and maintaining sustainable agricultural systems [15]. Spatial variability mapping can inform sustainable agroecosystem management by identifying areas requiring specific interventions, such as targeted fertilization or soil amendments [16]. Local observations in the Sebseb region also suggest that soils in areas where *R. raetam* naturally grows exhibit greater fertility, often supporting improved crop growth and productivity. Karaoud and Noumi [17] found that *R. raetam* enhances soil water availability, improves soil nutrient content (organic matter, total carbon, total nitrogen, and available phosphorus), and promotes understory vegetation in arid environments. Despite its importance, the interactions between *R. raetam* and soil parameters, as well as the spatial variability of these parameters, remain insufficiently understood.

This study is an integral part of a broader research effort to unravel the complex interactions between Fabaceae species and their rhizospheric environment, with a particular focus on Plant Growth-Promoting Rhizobacteria (PGPR). A comprehensive understanding of these plant-soil-microbe dynamics is fundamental for promoting sustainable agricultural practices and advancing ecological conservation. The research initiative seeks to unravel the complexity of how Fabaceae plants and the rhizosphere engage in mutualistic relationships by studying the interactions among rhizosphere and bulk soil parameters and their spatial variability of *R. raetam* collected in the region of Sebseb (Algeria), in order to better understand its role in soil fertility and potential contributions to sustainable land management.

Materials And Methods

Study area

The study was carried out in the Sebseb region, located in Ghardaïa Province, in the center of southern Algeria (approximately 32°15'N, 3°26'E) (Figure 1). The region is characterized by an arid Saharan climate with significant temperature fluctuations between day and night and between seasons. The hot season extends from May to September, with July the hottest month, averaging 36.3°C and reaching 47°C. In contrast, January is the coldest

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month, with an average temperature of 9.2°C and an absolute minimum of –1°C. Annual precipitation is scarce and irregular, ranging from 13 to 68 mm, spread over an average of 15 days per year. On average, the region receives around 74.2 mm of rainfall annually, with mean maximum and minimum temperatures of 28.5°C and 16.2°C, respectively [18].

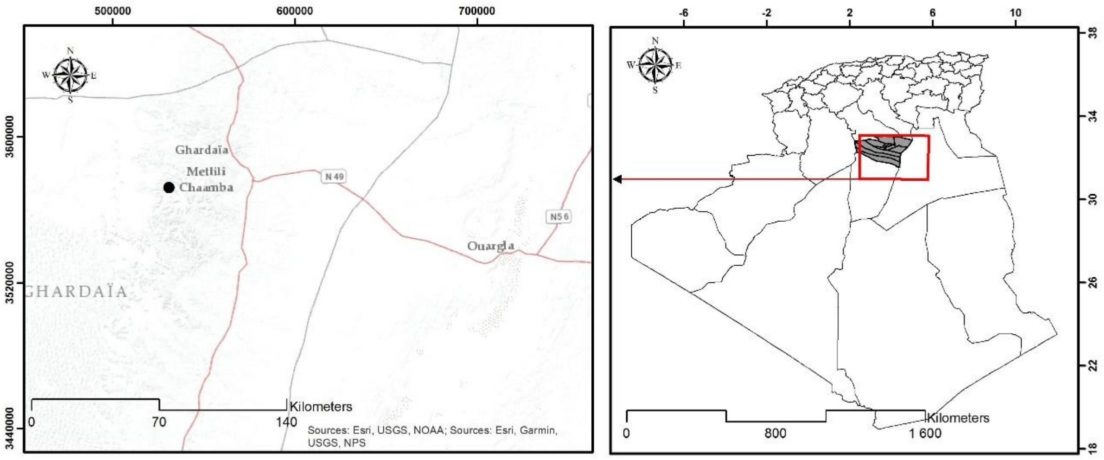

Figure 1. Geographical localization of the study area

Soil samples collection

Thirty-five (35) soil samples were collected during Spring 2023, from the rhizosphere and bulk soil. Using a trowel, the rhizosphere soil samples were obtained from areas directly influenced by plant roots. In contrast, bulk soil samples were collected from adjacent areas without direct root influence to provide a baseline for comparison. Samples were withdrawn at a depth of 20 cm below the surface in Ziplock plastic bags, which were then placed on ice and transported to the laboratory for further analysis.

Soil analysis

Soil samples were sieved through a 2-mm-mesh sieve. pH and EC at 25°C were determined in aqueous extract 1:5 (w/v). The $CaCO_3$ rate was tested using the Bernard calcimetry method described by [19]. The Loss on Ignition (LOD) method was used to determine OM content in soil. Approximately 5 g of sieved soil, weighed to the nearest 0.0001 g, was placed into pre-weighed porcelain crucibles and then dried in an oven at 220°C overnight. The crucibles containing the oven-dried soil were subjected to a second ignition step at 450°C for 4 hours, cooled, and weighed [19]. TN was measured using the Kjeldahl method from the standard operating procedure for soil nitrogen [20]. 3g of sieved soil was used as the sample size. NO_3-N was measured by the steam distillation method using Devarda's Alloy as described by [21]. AP was determined by UV spectrometry at 882-nm using the sodium bicarbonate ($NaHCO_3$) procedure of Olsen et al [22] as described in ICARDA manual [23]. 0.5M of sodium bicarbonate solution was used as extractant in 1:10 (w/v) ratio. Calibration concentrations ranged from 0.5 to 10 ppm of dried KH2PO4. TNa and TK were determined using a flame photometer according to the procedure described in the ICARDA manual [23]. 1N Ammonium Acetate (NH_4OAc) was used as the extraction solution with at 1:5 (w/v) ratio. SNa and SK were measured by the same method using an aqueous extract from a saturated paste. NaCl and KCl with concentrations ranging from 10 to 100 ppm were used to calibrate the flame photometer.

Statistical analysis

Statistical analyses were performed using the R programming language (R 4.5.1). Differences between RS and BS were assessed using independent two-sample t-tests, with $p < 0.05$ as the criterion for significance. Pearson correlation coefficients were computed to examine relationships among soil properties. Principal Component Analysis (PCA) was applied to reduce dimensionality, identify key variables influencing soil quality and fertility, and

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visualize the separation of RS and BS samples. Graphical outputs, including boxplots, correlation matrices, and PCA biplot, were used to illustrate the results.

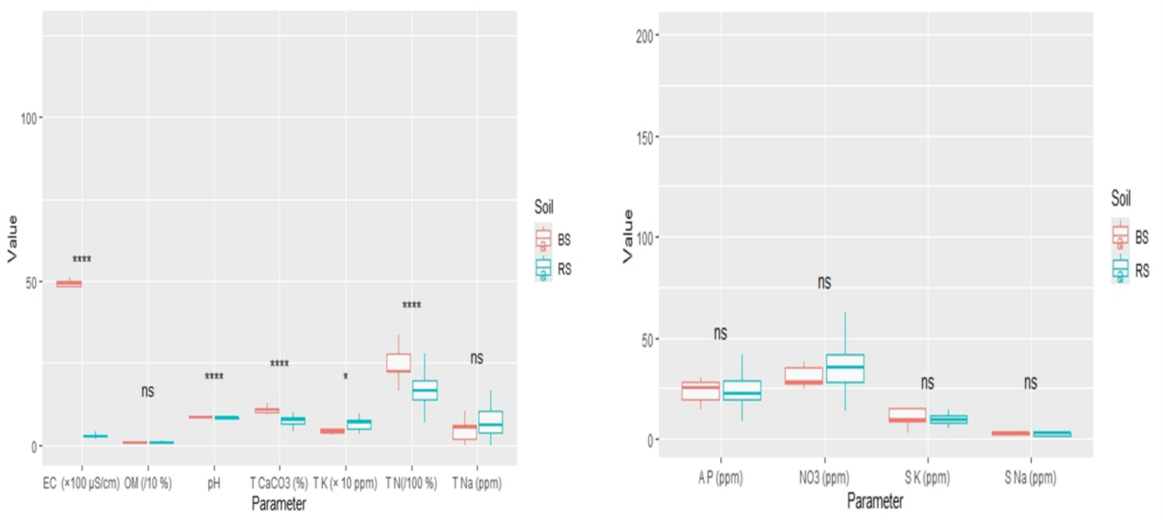
Geostatistical Analysis

Geostatistical methods were used to assess the spatial variability of soil parameters. Experimental semi-variograms were calculated for each variable to describe spatial dependence, and models (Gaussian, spherical, or exponential) were fitted based on the best agreement with the empirical data. Model selection was guided by minimizing residual sum of squares and maximizing the coefficient of determination (R^2). The nugget-to-sill ratio ($SDR=C_o/(C_o+C)\times 100$) was calculated to classify the degree of spatial dependence [24]. The range parameter was used to determine the spatial influence distance for each soil property. Ordinary kriging was applied to generate spatial distribution maps, allowing visualization of nutrient and property patterns across the study area. These maps were used to identify nutrient hotspots, gradients, and areas of spatial continuity, providing insight into localized rhizosphere processes and broader pedogenic control.

Results

Comparative analysis of rhizosphere and bulk soil

To determine significant differences in properties between RS and BS, statistical t-tests were conducted. The results are visually represented in the corresponding boxplots (Figure 2). The comparison of soil properties between RS and BS revealed significant differences in several key characteristics. EC ($p < 0.0001$) and $CaCO_3$ ($p < 0.0001$) content were significantly higher in BS. Similarly, TN content was significantly higher in BS ($p = 0.0069$). Whilst RS exhibited a significantly lower pH ($p < 0.0001$). NO3 ($p = 0.01$) and TK ($p = 0.01$) levels were also significantly different, with RS having higher concentrations than BS. In contrast, SK, SNa, AP, and OM showed no significant differences between the two soils ($p > 0.05$).



(a) EC, OM, pH, $CaCO_3$, TK, TN and TNa (b) AP, NO_3, SK and SNa

Figure 2. boxplot showing the significant differences between RS and BS

Principal component analysis and correlation matrix

Principal component analysis (PCA) was performed to identify relationships among soil physicochemical parameters in the rhizosphere. The first two axes explained 62.4% of the total variance, with Dim1 accounting for

40.2% and Dim2 for 22.2% (Figure 3). Variables such as EC, TNa, pH, and AP were grouped on the positive side of Dim1. In contrast, CaCO3 was positioned on the negative side of Dim1. Along Dim2, OM and SNa clustered closely together, while SK and TK formed another tight group. NO3 and TN were separated from the main clusters, with NO3 located in the negative quadrant of both axes.

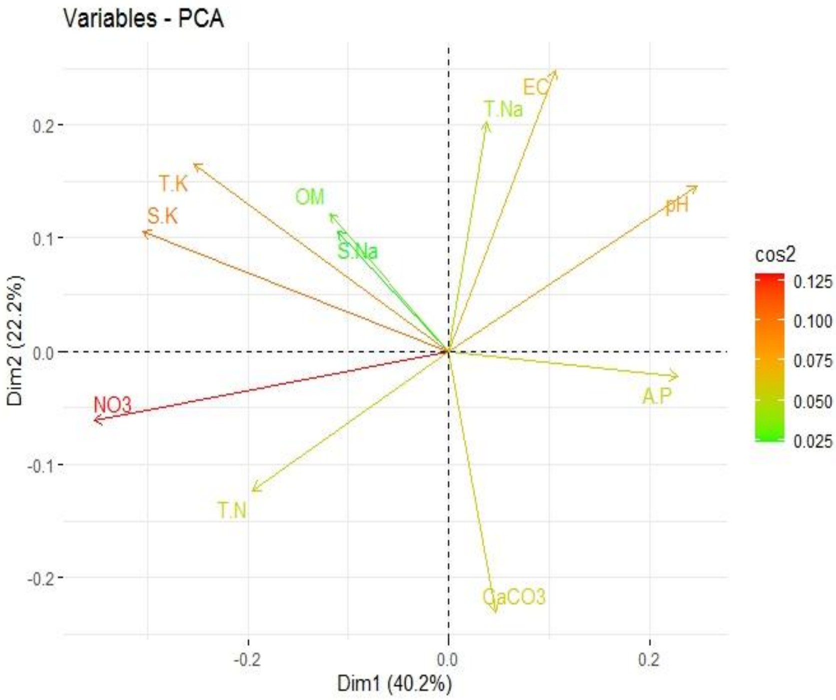


Figure 3. Principal Components Analysis (PCA) of soil parameters

The correlation matrix revealed several significant relationships between rhizosphere soil properties. SNa showed a significant positive correlation with MO (r = 0.3624, p = 0.0491), TNa (r =0.3670, p = 0.0461), TK (r = 0.4296, p = 0.0178), TN (r = 0.4471, p = 0.0132). SK showed a significant positive correlation with NO3 (r = 0.4282, p = 0.0182). TK showed a significant positive correlation with TNa (r = 0.4171, p = 0.0218), SK (r = 0.8569, p < 0,0001), NO_3 (r = 0.4655, p = 0.0095) and EC (r = 0.4223, p = 0.0201). TNa showed a significant positive correlation with EC (r = 0.3957, p =0.0304), SK (r = 0.3796, p = 0.0385) (Figure 4).

Geostatistical analysis of rhizosphere soil parameters

The spatial variability of soil parameters was evaluated through variogram modeling and the coefficient of variation (CV%), as summarized in Table 1. All variables followed a Gaussian distribution, whereas EC, pH, SNa, and TNa were better fit by spherical distributions, indicating spatial heterogeneity. The nugget-to-sill ratios for all variables were below 25%. The range values varied substantially. Parameters such as OM (2.5 m), SK (3.6 m), and TNa (4 m) showed limited spatial influence; in contrast, AP (2119 m), NO3 (1643 m), and CaCO3 (20 m) had longer spatial ranges. High CV values were observed for AP (0.87) and TN (0.87). Moderate variability was observed for OM (0.47) and TNa (0.66), while pH (0.036) and EC (0.22) had lower CVs.

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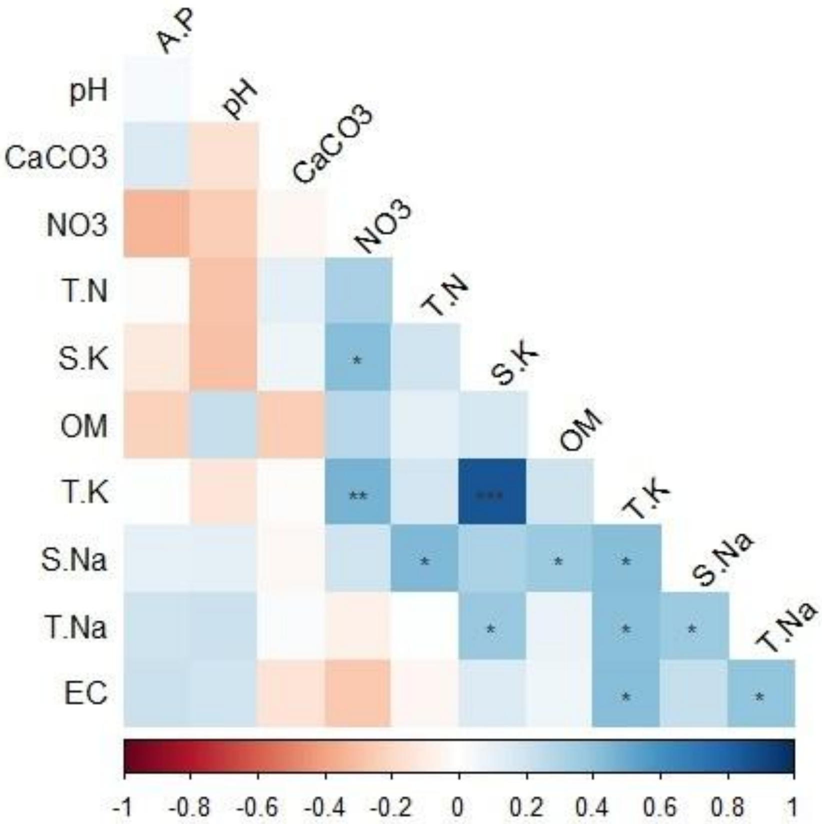

Figure 4. Correlation matrix with significant relationship of rhizosphere soil properties

Table 1. Fitted variogram models and variation properties

Parameter	Model	Nugget	Sill	Range (m)	Nugget/Sill (%)	Coefficient of variation (%)
AP	Gaussian	81	3515946	2119	~0.002	86.98
$CaCO_3$	Gaussian	0.83	11	20	7.5	29.61
NO_3	Gaussian	48	251562	1643	~0.019	31.44
TN	Gaussian	0	0.03	9.1	0	86.95
EC	Spherical	0	3485	10	0	21.76
OM	Gaussian	0	0.06	2.5	0	47.12
pH	Spherical	0.02	0.11	27	18.2	3.64
SK	Gaussian	0	5.3	3.6	0	26.12
SNa	Spherical	0	0.96	4.9	0	35.03
TK	Gaussian	7.7	375	7.2	2.1	29.06
TNa	Spherical	0	17	4	0	66.20

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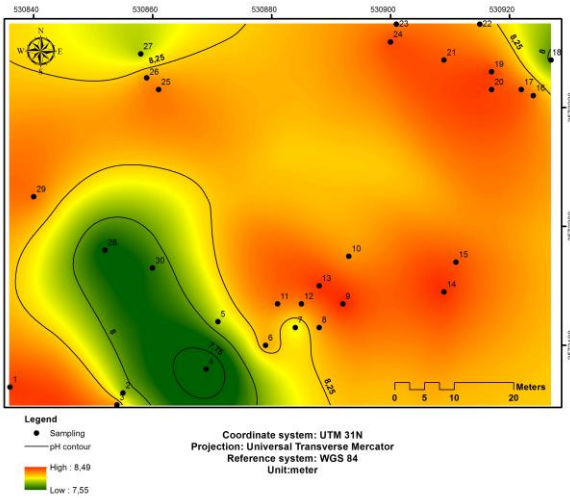
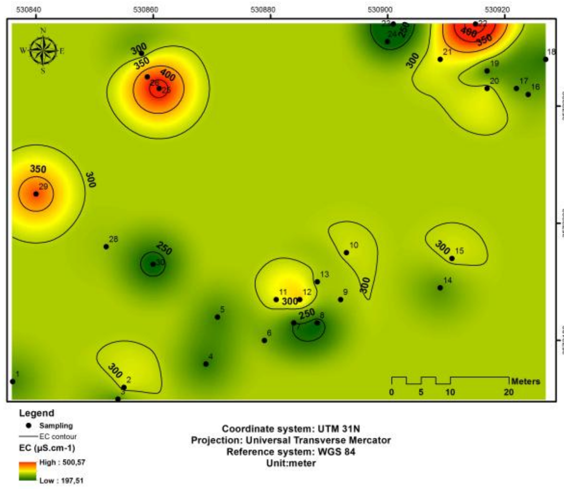
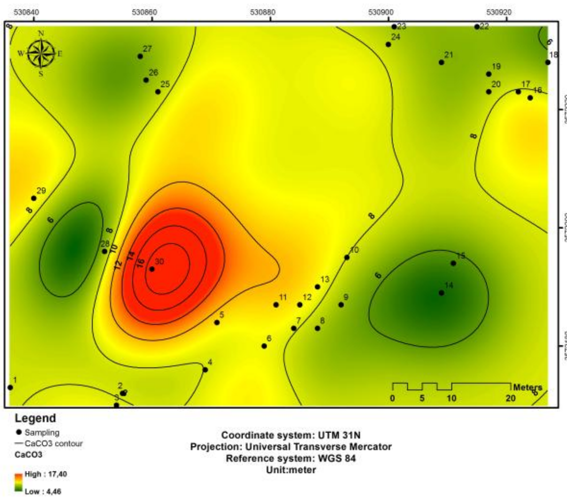
The spatial distribution maps generated by ordinary kriging revealed distinct patterns of soil property variability across the study area. $CaCO_3$ content ranged from 4.46% to 17.40%, with the highest concentrations observed in the south-central region. EC ranged from 197.51 to 500.57 $\mu S \cdot cm^{-1}$, indicating localized salinity hotspots in the northwest, northeast, and southwest. AP levels ranged from 9.33 to 127.94 ppm, with markedly higher values in the northwest, while lower concentrations predominated in the central and eastern regions. NO_3 concentrations ranged from 19.44 to 61.94 ppm, with elevated levels occurring in the south-central area. Soil pH values showed slight variation, ranging from 7.55 to 8.49, with more alkaline zones located in the northeastern and central regions (Figure 5).



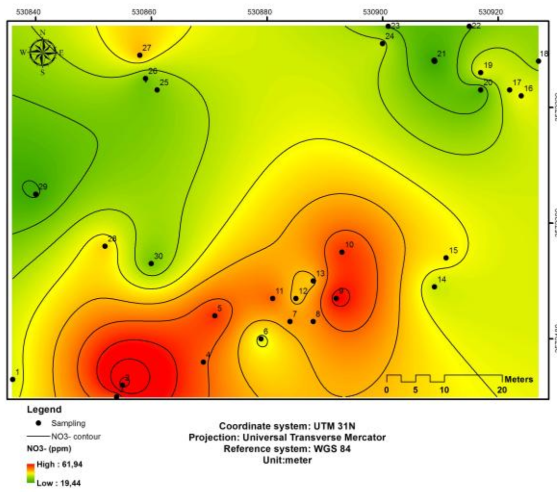
(a) pH



(b) EC



(c) $CaCO_3$



(d) NO_3^-

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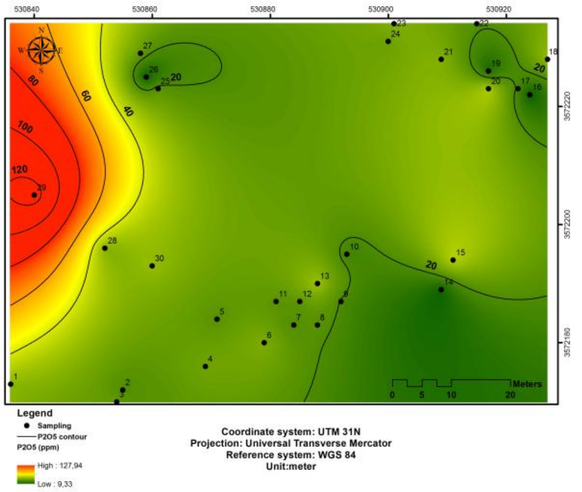

(e) P_2O_5

Figure 5. Spatial distribution maps generated by ordinary kriging for rhizosphere soil parameters

DISCUSSION

Rhizosphere and Bulk Soil properties

The microbial community in the rhizosphere is generally more active and diverse than in bulk soil [25], and this activity strongly influences the chemical environment, including electrical conductivity (EC). Microbial processes modify nutrient availability and ion concentrations, often lowering EC in the rhizosphere compared to the surrounding soil [26]. In line with this, our results showed significantly higher EC in bulk soil ($p < 0.0001$), a trend also reported in previous studies [27, 28]. Such reductions in rhizosphere EC are likely due to enhanced ion uptake and microbial transformations. Additionally, practices such as incorporating legumes as green manure further enrich soil organic matter, improve nutrient cycling, and help stabilize EC while promoting sustainable agriculture [29]. Furthermore, EC and pH also differed significantly between soil compartments, with rhizosphere soil showing lower values than bulk soil ($p < 0.0001$). This pattern is widely supported by evidence across diverse cropping systems, including paddy soils [30], neutral or alkaline soils [31], and more recent studies documenting significant rhizosphere acidification [32, 33]. The decrease in rhizosphere pH is primarily linked to root proton release and microbial activity, while in species such as Retama raetam, organic matter inputs from leaf litter and root residues may release organic acids during decomposition, further enhancing acidification. Conversely, the release of certain organic anions during decomposition may increase pH through decarboxylation and base release, reflecting the complex interplay of rhizosphere processes [34, 35]. These conditions also shape nitrogen dynamics: our results indicated that nitrate concentrations were significantly higher in rhizosphere soil ($p = 0.01$), consistent with studies reporting enhanced microbial activity, nitrogen fixation by Rhizobiaceae, and increased N-cycling enzyme activity in legume rhizospheres, leading to greater nitrogen availability compared to bulk soil [36-38]. In contrast, total nitrogen was significantly higher in bulk soil ($p = 0.0069$). This finding agrees with results from alpine grasslands where rhizosphere total nitrogen was lower than in bulk soil [39], suggesting that the rhizosphere effect is highly species- and environment-dependent. Similarly, our study found that $CaCO_3$ content was significantly higher in bulk soil ($p < 0.0001$), a result consistent with reports showing that carbonate content tends to decrease in the rhizosphere due to root-driven CO_2 enrichment and acidification, with the highest levels retained in bulk soil [40]. Collectively, these findings highlight that rhizosphere processes driven by root activity, microbial interactions, and organic matter turnover create distinct chemical signatures that differentiate rhizosphere from bulk soil in terms of EC, pH, nitrogen dynamics, and $CaCO_3$ distribution.

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Multivariate Analysis

In this study, several significant correlations among soil properties were observed, consistent with previous research. Soluble sodium showed a positive correlation with both organic matter ($r = 0.3624$, $p = 0.0491$) and total sodium ($r = 0.3670$, $p = 0.0461$). Similar patterns have been widely documented, with numerous studies demonstrating that soluble and total sodium tend to increase under varying soil types and conditions, including saline and agricultural environments [41, 42]. Sodium salts are also known to enhance organic matter release, as sodium exchange processes displace sorbed organic anions, thereby promoting solubilization [43]. Moreover, positive associations between organic matter and soil aggregate stability, where sodium plays a role alongside organic inputs, highlight the contribution of soluble sodium to structural processes in soils [44]. In terms of nutrients, soluble potassium correlated positively with nitrate ($r = 0.4282$, $p = 0.0182$), a relationship also reported in agricultural soils, where fertilization practices and crop uptake coordinate K^+ and NO_3^- dynamics [45-47]. This coordination reflects the physiological role of potassium as a counter-ion facilitating nitrate transport in plants [48]. Field evidence further shows synchronized increases of nitrate and potassium under fertilization [45], as well as positive associations between extractable soil potassium, nitrate, and plant performance in vineyards [46], and in restored soils where nutrient mineralization links sodium and nitrogen forms [49]. Total potassium exhibited strong correlations with soluble potassium ($r = 0.8569$, $p < 0.0001$), NO_3^- ($r = 0.4655$, $p = 0.0095$), and EC ($r = 0.4223$, $p = 0.0201$), reinforcing the idea of a dynamic equilibrium among potassium fractions. Similar positive associations among different forms of potassium have been reported in the Lesser Himalayas [50], Haryana and North Bihar [51, 52], paddy soils of Nagpur [53], and acid Alfisols [54]. Additionally, the link between total potassium and EC reflects the well-established role of potassium in salinity contexts, with strong correlations ($r \geq 0.83$) documented in arid and saline-sodic soils [55]. Similarly, total sodium correlated positively with EC ($r = 0.3957$, $p = 0.0304$) and soluble potassium ($r = 0.3796$, $p = 0.0385$), in agreement with studies reporting extremely strong associations ($r > 0.95$) between sodium, potassium, and EC in saline soils of Libya and Oman [56-58] Collectively, these results emphasize that sodium and potassium dynamics are closely linked to each other and to nitrogen and salinity indicators, and that these interrelationships are mediated by soil chemical processes, fertilization practices, and plant uptake patterns across environments.

Rhizosphere soil variability

Geostatistical analysis has long been recognized as a powerful approach for characterizing soil spatial variability, with ordinary kriging and semivariogram modeling widely applied in this context. Previous studies often reported that spherical and exponential models provide the best fit for soil properties [59, 60]. In contrast, our results showed that most soil parameters were better represented by a Gaussian model, whereas only EC, pH, soluble sodium, and total sodium were better described by a spherical model. These differences indicate that spatial dependence varies across soil attributes, reinforcing the importance of careful model selection to capture gradual versus localized patterns of variability. Both Gaussian and spherical models are well established in soil science, having been successfully applied to describe the spatial patterns of pH, EC, and nutrient distribution across different environments [61-63].

The nugget-to-sill ratio, also known as the spatial dependence ratio (SDR), was calculated for all parameters as described in [24]. According to the classification of [64], values below 25% indicate strong spatial dependence, between 25% and 75% moderate, and above 75% weak dependence. In our study, all soil properties showed SDR values below 25%, indicating strong spatial dependence. This implies that the observed variability is mainly structured and controlled by soil-forming processes and biological activity, rather than by random error or micro-scale heterogeneity.

The spatial ranges of different parameters further illustrate their controlling mechanisms. For instance, OM (2.5 m), SK (3.6 m), and TNa (4 m) exhibited short ranges, suggesting localized variability likely linked to root activity, microbial hotspots, or other small-scale biological processes. Nonetheless, AP (2119 m), NO_3^- (1643 m), and $CaCO_3$ (20 m) had longer ranges, reflecting the influence of broader pedogenic or environmental drivers that extend across the landscape.

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The coefficient of variation (CV) provided an additional measure of variability. Following [65] 's classification, parameters such as AP (0.87) and TN (0.87) showed high variability, likely due to uneven nutrient cycling or plant uptake. OM (0.47) and TNa (0.66) exhibited moderate variability, while pH (0.036) and EC (0.22) were relatively uniform across the study area. Interestingly, even parameters with low CVs, such as pH, still showed structured patterns in their variograms, indicating that uniform variance does not necessarily imply spatial randomness [66].

CONCLUSION

This study highlights the influence of Retama raetam on soil properties and their spatial variability in the arid region of Sebseb, Algeria. Rhizosphere soil was characterized by lower pH and higher nitrate, while bulk soil contained higher EC, $CaCO_3$, and total nitrogen, reflecting contrasting biological and pedogenic processes. Strong correlations among sodium, potassium, organic matter, and nitrate confirmed the interconnectedness of nutrient pools.

Geostatistical analysis revealed structured variability, with all parameters fitting Gaussian or spherical models and nugget-to-sill ratios less than 25%, indicating strong spatial dependence. Short-range variability in organic matter, soluble potassium, and total sodium reflected localized rhizosphere processes, whereas longer-range variability in available phosphorus, nitrate, and $CaCO_3$ was influenced by broader environmental factors.

Overall, Retama raetam plays a key ecological role in acidifying soils and enhancing nutrient availability in arid shrublands. The combination of GIS and geostatistical approaches provided valuable insights into multi-scale soil heterogeneity and supports the role of spontaneous Fabaceae shrubs as natural contributors to soil fertility and sustainable land management.

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