**Peruvian Journal of Agronomy**
http://revistas.lamolina.edu.pe/index.php/jpagronomy/index

**RESEARCH ARTICLE**
https://doi.org/10.21704/pja.v9i2.2030

Received for publication: 8 May 2025
Accepted for publication: 20 June 2025
Published: 15 July 2025
ISSN: 2616-4477


# Chemical properties and mineral nutrient content within and outside the rhizosphere of corn (*Zea mays*) in an Andean soil of Peru

# Propiedades químicas y contenido de nutrientes minerales dentro y fuera de la rizósfera del maíz (*Zea mays*) en un suelo andino del Perú

Klaus P. RAVEN WILLWATER[1,*]; Constantino S. CALDERÓN MENDOZA[1]

[1]Universidad Nacional Agraria La Molina, Faculty of Agronomy, Department of Soils, Av. La Molina s/n, Lima-Perú.

*Corresponding author: kpraven@lamolina.edu.pe
https://orcid.org/0009-0001-8533-8910

## Abstract

The rhizosphere is the medium in which plant roots live. Its study began more than 100 years ago. Nowadays, this topic continues to attract the interest of researchers due to its complexity and repercussions on land ecology, natural resources sustainability, and food security. Nutrient availability in the rhizosphere has been extensively studied. However, most studies have focused on a few parameters that were evaluated in detail. The objective of this research was to compare the chemical properties and availability of all essential mineral nutrient elements for higher plants, except Mo and Ni, between rhizospheric soil and soil not affected by root activity. This comparison was intended to be thorough in order to obtain a picture of how different rhizospheric and bulk soils really are. For this purpose, samples of both soil types were collected in a corn (*Zea mays*) field at the Oyolopampa farm (Ayacucho, Peru). These were analyzed for general chemical properties and soluble and available concentrations of each nutrient element. The rhizospheric soil in the Oyolopampa corn field differed from the bulk soil in 31 % of the 29 evaluated chemical properties. Thus, the total solute concentration, available $NH_4^+$, soluble and available K, soluble Mg, soluble and available B, and soluble Cl were higher in the rhizospheric soil, while available Cu was higher in the bulk soil. Our results and literature survey showed that the chemical properties of the rhizospheric soil could have higher, similar, or lower values than the bulk soil, with the possible exceptions of salinity and soluble Cl content. The differences between these soil types were therefore case-specific and depended on the evaluated property or substance, plant genotype, soil properties, environmental conditions, and moment of examination.

*Keywords: Soil, root, rhizosphere, Zea mays, mineral nutrient.*

## Resumen

La rizósfera es el medio en el que viven las raíces de las plantas. Su estudio se inició hace mas de 100 años. Actualmente, este tema sigue atrayendo el interés de investigadores por su complejidad y repercusiones sobre la ecología terrestre, sostenibilidad de recursos naturales y seguridad alimentaria. La disponibilidad de nutrientes minerales en la rizósfera ha sido extensamente estudiada. Sin embargo, la mayoría de estudios se enfocaron en unos pocos parámetros que fueron evaluados en detalle. El objetivo de esta investigación fue comparar las propiedades químicas y disponibilidad de todos los elementos nutritivos minerales esenciales para plantas superiores, excepto Mo y Ni, entre suelo rizosférico y suelo no afectado por la actividad de raíces.

**How to cite this article:**
Raven, K., & Calderón, C. (2025). Chemical properties and mineral nutrient content within and outside the rhizosphere of corn (*Zea mays*) in an Andean soil of Peru. *Peruvian Journal of Agronomy, 9*(2), 90-103. https://doi.org/10.21704/pja.v9i2.2030

La comparación tuvo la intención de ser detallada con el fin de obtener una idea del grado de discrepancia real entre suelo rizoférico y aquel no afectado por las raíces. Para ello, se colectaron muestras de ambos tipos de suelo en un campo de maíz (*Zea mays*) en el fundo Oyolopampa (Ayacucho, Perú). En estas se determinaron propiedades químicas generales y concentraciones solubles y disponibles para cada elemento nutritivo. El suelo rizosférico del campo de maíz de Oyolopampa discrepó del suelo no afectado por raíces en 31 % de las 29 propiedades químicas evaluadas. Así, la concentración total de solutos, $NH_4^+$ disponible, K soluble y disponible, Mg soluble, B soluble y disponible y Cl soluble fueron mayores en el suelo rizosférico, mientras que el Cu disponible fue mayor en el suelo no alterado por raíces. Nuestros resultados y revisión de literatura demostraron que las propiedades químicas del suelo rizosférico podían tener valores superiores, similares o inferiores que el suelo no afectado por raíces, excepto posiblemente la salinidad y contenido de Cl soluble. Por ello, las diferencias entre ambos tipos de suelos fueron específicas para cada caso y dependieron de la propiedad o sustancia evaluada, genotipo vegetal, propiedades del suelo y momento de evaluación.

*Palabras clave: Suelo, raíz, rizósfera, Zea mays, nutriente mineral.*

## Introduction

The concept of rhizosphere was proposed in 1904 by Hiltner to refer to the soil volume surrounding individual plant roots that is influenced by their activity (Neumann & Ludewig, 2023). The original report emphasized the interaction between roots and the adjacent soil microorganisms. This aspect is still extensively being studied at present (Ling et al., 2022; Pantigoso et al., 2022; Marschner, 2023; Thakur et al., 2024). The rhizosphere also has specific physical features (Helliwell et al., 2019; Adamczewski et al., 2024) and special chemical characteristics. The latter include general soil chemical properties and those related to the availability of mineral nutrients and toxic substances to plants (Neumann & Ludewig, 2023). In the past, all these aspects have been mainly studied and evaluated individually. It has been proposed to make an integral evaluation and interpretation of these components and, ideally, carry them out at various scales to acquire a better understanding of the rhizosphere and its effects upon plant growth and development (York et al., 2016; Schnepf et al., 2022).

Since the rhizosphere is the habitat of roots, it is also important for plant growth and development. This fact has consequences on the ecology at the earth's surface, natural resources sustainability, and food security (Wang et al., 2022; Solomon et al., 2024). To improve and optimize these aspects, rhizosphere engineering has gained interest (Dessaux et al., 2016; Ahkami et al., 2017).

The chemical properties and mineral nutrient availability in the rhizosphere have been previously studied (Neumann & Ludewig, 2023). Nevertheless, this subject keeps on drawing the attention of researchers because of its complexity and the variability among findings. In addition, most studies have dealt with a few rhizosphere properties that were evaluated in more detail. Therefore, more knowledge has accumulated about some nutrient elements, such as N, P, K and Ca, but very little information is available about other elements, including S and B. In addition, differences between rhizospheric and bulk soils have been commonly judged from limited sets of chemical properties.

The objective of this research was to compare basic chemical properties and mineral nutrient availability between rhizospheric and bulk soil in a corn (*Zea mays*) field. In contrast to previous studies, all essential mineral nutrient elements for higher plants, except Mo and Ni, were evaluated, including those that have been poorly documented in the past. Furthermore, soluble and available nutrient fractions were compared. Performing a comparison with so many variables will yield a more complete picture of how different rhizospheric and bulk soils actually are and is rarely found in the literature.

## Materials and methods

A field experiment with a local unnamed corn variety, 3 soil treatments, and 3 repetitions per treatment was installed at the Oyolopampa farm (Páucar del Sara Sara, Ayacucho, Peru) in September 2023. The elevation of this site was about 3 400 m AMSL, and its approximate geographic coordinates were 15°10'46" S and 73°11'6" W. The local soil formed on an andic residual parent material and has not been formally classified. The surface soil had loamy texture and moderate, medium, granular structure. The

average rainfall in the region was about 800 mm $y^{-1}$, and the mean annual temperature was around 16 °C. The crop was organically farmed with supplemental flood irrigation. The soil treatments were: none (control), addition of sheep manure (5 $t.ha^{-1}$), and addition of sheep manure (5 $t.ha^{-1}$) with seabird guano (0.5 $t.ha^{-1}$). The experimental design was a 3 x 3 latin square. The latin square design was chosen due to the presence of 2 perpendicular slope components in the field.

During the first days of February 2024, samples of rhizospheric and bulk soils were taken from each of the 9 plots of the field experiment. At this time, the corn plants were at the kernel milk stage (R3). Bulk soil was extracted from the upper 0.2 m of the soil in randomly selected places that were not occupied by corn plants. Rhizospheric soil was obtained by excavating the upper 0.2 m of the root system from randomly selected corn plants, followed by shaking off the bulk soil and collecting the remaining soil that was adjacent to the roots.

The preparation of the 18 soil samples for chemical analyses was started in Ayacucho and ended in Lima. The procedure included: air-drying under shade, clod crushing, mixing, sieving, and collecting the fine earth fraction (<2 mm particle diameter).

Chemical analyses of the soil samples were carried out at the Laboratorio de Análisis de Suelos, Plantas, Aguas y Fertilizantes (LASPAF) of the Faculty of Agronomy of Universidad Nacional Agraria La Molina. Five basic soil chemical properties were evaluated. pH was measured potentiometrically in the saturated soil paste. Salinity was assessed by the electrical conductivity of the soil saturation extract. Easily oxidizable C was quantified by the Walkley & Black method with titration of the dichromate excess. Effective cation exchange capacity (CEC) was calculated by adding up the concentrations of exchangeable $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$, $NH_4^{+}$, and acidity in the soil samples (see below). Extractable (or exchangeable) acidity was measured by NaOH titration of the KCl soil extract. Additionally, 24 mineral nutrient element availability indexes were evaluated. Soluble K, Ca, Mg, Fe, Mn, Zn, and Cu were assessed by atomic absorption spectrophotometry of the soil saturation extract. Soluble $NO_3^{-}$-N, P, $SO_4^{2-}$-S, B, and Cl were quantified by colorimetry using salicylic acid, colorimetry using sulfomolybdate, turbidimetry using $BaCl_2$, colorimetry using curcumin, and $AgNO_3$ titration, respectively, of the soil saturation extract. Available (or exchangeable) K, Ca, Mg, and Na were measured by atomic absorption spectrophotometry of the ammonium acetate soil extract. Available (or exchangeable) $NH_4^{+}$-N was extracted from soil with KCl and analyzed by the micro-Kjeldahl method. Available Fe, Mn, Zn, and Cu were assessed by atomic absorption spectrophotometry of the $NaHCO_3$-EDTA-$NH_4F$ soil extract. Available P was quantified by Olsen's method. Available $SO_4^{2-}$-S was measured by turbidimetry (using $BaCl_2$) of the $NH_4Cl$ soil extract. Available B was assessed by colorimetry (using curcumin) of the $Ca(H_2PO_4)_2$-HCl soil extract. Finally, total N was determined by the micro-Kjeldahl method using the entire soil sample. The specific procedures that were used have been published by Bazán (1996).

The statistical evaluation of the soil data was carried out by expanding the original 3 x 3 latin square to a split-plot design, with soil treatments in wholeplots and soil types (bulk and rhizospheric) in subplots. Sources of variation in the analysis of variance (AOV) included: rows, columns, soil treatments (Tr), wholeplot error, soil types (Ty), Tr x Ty interaction, subplot error, and total. The respective degrees of freedom were: 2, 2, 2, 2, 1, 2, 6, and 17. The F tests for Ty factor, Tr x Ty interaction, and simple effects of Ty within Tr used the subplot error mean square (SPE), as described by Ott & Longnecker (2016). When the variability of the results for a given soil property was high, the consistency of the differences between both soil types in the 9 wholeplots was evaluated by applying the nonparametric Wilcoxon signed-rank test to the respective paired data, as outlined by Ott & Longnecker (2016).

## Results and discussion

The factors Tr and Ty had independent effects for all the evaluated parameters, since the Tr x Ty interaction was not statistically significant for any one of them (Tables 1 to 3). Therefore, rhizospheric and bulk soils could be directly compared through the F test for the Ty factor.

The coefficients of variation for subplots (CVS) of the evaluated properties spanned greatly between 1.8 and 197.8 % (Tables 1 to 3). If an F test is performed with a relatively low SPE, which corresponds to a small CVS, there exists a risk of declaring as significant a mean difference that might not have real importance. On the other hand, if an F test is carried out with a rather high SPE, which corresponds to a large CVS, it is possible that an important mean difference is not designated as significant. Therefore, the percentages of the differences between rhizospheric and bulk soils for each evaluated parameter were also considered. Their values ranged from <0.1 % to 181.8 % (Tables 1 to 3). Given these interpretation issues, a difference between the means of both soil types was considered of real importance if: (i) it was statistically significant and 35 % > CVS > 10 %, or (ii) it did not reach statistical significance, CVS ≥ 35 %, percent difference between means > 10 %, and differences were consistent in the 9 wholeplots of the experiment as assessed by Wilcoxon's test.

**Table 1.** Basic chemical properties and N and P availability indexes of bulk (B) and rhizospheric (R) soil samples and statistical results.

| Parameter | Averages | | | Statistical Test[2] and Significance[3] | | | Coefficient of Variation for Subplots |
|---|---|---|---|---|---|---|---|
| | B | R | Difference (%)[1] | Interaction Tr[4] x Ty[4] | Factor Ty[4] | Wilcoxon | (%) |
| pH (unitless) | 4.23 | 4.35 | 2.8 | 0.19 NS | 11.24 ** | - | 1.8 |
| Salinity (dS.m$^{-1}$) | 0.44 | 0.51 | 15.9 | 0.40 NS | 4.73 * | - | 15.7 |
| Easily Oxidizable C (g.kg$^{-1}$) | 13.8 | 13.8 | 0.3 | 3.01 NS | <0.01 NS | - | 13.6 |
| Effective CEC (cmol$_c$.kg$^{-1}$) | 13.7 | 14.1 | 2.9 | 0.03 NS | 1.32 NS | - | 5.2 |
| Extractable Acidity (cmol$_c$.kg$^{-1}$) | 0.43 | 0.34 | 26.5 | 1.25 NS | 1.56 NS | n=8, 7 NS | 41.5 |
| Soluble $NO_3^-$-N (mg.kg$^{-1}$) | 4.95 | 8.12 | 64.0 | 1.09 NS | 2.80 NS | n=9, 10 NS | 61.6 |
| Available $NH_4^+$-N (mg.kg$^{-1}$) | 17.4 | 21.8 | 25.0 | 0.58 NS | 5.94 * | - | 19.3 |
| Total N (g.kg$^{-1}$) | 2.08 | 2.08 | <0.1 | 0.93 NS | <0.01 NS | - | 5.6 |
| Soluble P (mg.kg$^{-1}$) | 0.0148 | 0.0417 | 181.8 | 0.67 NS | 1.04 NS | n=5, 5 NS | 197.8 |
| Available P (mg.kg$^{-1}$) | 33.1 | 34.9 | 5.2 | 1.05 NS | 0.30 NS | - | 19.7 |

Notes:
[1]With respect to the smaller value
[2] F tests for Tr x Ty interaction and Ty factor in the AOV and Wilcoxon's test for n paired data of 9 subplots with T statistic value
[3]Not significant (NS) for p≥0,10 or significant for 0.10>p≥0.05 (*),0.05>p≥0.01 (**), or p<0.01 (***)
[4]Factors: Tr (soil treatments, in wholeplots) y Ty (soil types, in subplots)

**Table 2.** K, Ca, Mg, S, and Fe availability indexes of bulk (B) and rhizospheric (R) soil samples and statistical results.

| Parameter | Averages | | | Statistical Test[2] and Significance[3] | | | Coefficient of Variation for Subplots |
|---|---|---|---|---|---|---|---|
| | B | R | Difference (%)[1] | Interaction Tr[4] x Ty[4] | Factor Ty[4] | Wilcoxon | (%) |
| Soluble K (mg.kg$^{-1}$) | 7.27 | 9.41 | 29.4 | 0.57 NS | 9.06 ** | - | 18.1 |
| Available K (mg.kg$^{-1}$) | 446 | 507 | 13.8 | 0.75 NS | 6.81 ** | - | 10.5 |
| Soluble Ca (mg.kg$^{-1}$) | 16.7 | 18.5 | 11.0 | 0.91 NS | 1.59 NS | - | 17.7 |
| Available Ca (mg.kg$^{-1}$) | 1910 | 1947 | 1.9 | 0.04 NS | 0.53 NS | - | 5.6 |
| Soluble Mg (mg.kg$^{-1}$) | 3.21 | 4.12 | 28.4 | 0.17 NS | 7.54 ** | - | 19.3 |
| Available Mg (mg.kg$^{-1}$) | 290 | 302 | 4.0 | 0.37 NS | 1.25 NS | - | 7.5 |
| Soluble S-$SO_4^{2-}$ (mg.kg$^{-1}$) | 1.80 | 1.26 | 42.9 | 0.53 NS | 1.32 NS | n=8, 10 NS | 64.9 |
| Available S-$SO_4^{2-}$ (mg.kg$^{-1}$) | 44.4 | 45.9 | 3.3 | 0.05 NS | 0.10 NS | - | 21.6 |
| Soluble Fe (mg.kg$^{-1}$) | 0.0272 | 0.0258 | 5.4 | 1.55 NS | 0.06 NS | - | 45.8 |
| Available Fe (mg.kg$^{-1}$) | 357 | 358 | 0.5 | 1.90 NS | 0.04 NS | - | 5.1 |

Notes:
[1]With respect to the smaller value
[2] F tests for Tr x Ty interaction and Ty factor in the AOV and Wilcoxon's test for n paired data of 9 subplots with T statistic value
[3]Not significant (NS) for p≥0,10 or significant for 0.10>p≥0.05 (*),0.05>p≥0.01 (**), or p<0.01 (***)
[4]Factors: Tr (soil treatments, in wholeplots) y Ty (soil types, in subplots)

**Table 3.** Mn, Zn, Cu, B, and Cl availability indexes of bulk (B) and rhizospheric (R) soil samples and statistical results.

| Parameter | Averages | | | Statistical Test[2] and Significance[3] | | | Coefficient of Variation for Subplots |
|---|---|---|---|---|---|---|---|
| | B | R | Difference (%)[1] | Interaction Tr[4] x Ty[4] | Factor Ty[4] | Wilcoxon | (%) |
| Soluble Mn (mg.kg$^{-1}$) | 0.411 | 0.459 | 11.7 | 0.77 NS | 0.18 NS | n=9, 22 NS | 55.8 |
| Available Mn (mg.kg$^{-1}$) | 190 | 206 | 8.2 | 0.23 NS | 12.12 ** | - | 4.8 |
| Soluble Zn (mg.kg$^{-1}$) | 0.138 | 0.124 | 11.1 | 3.20 NS | 0.39 NS | n=9, 27 NS | 35.8 |
| Available Zn (mg.kg$^{-1}$) | 3.30 | 3.26 | 1.2 | 0.26 NS | 0.27 NS | - | 5.0 |
| Soluble Cu (mg.kg$^{-1}$) | 0.0032 | 0.0026 | 23.1 | 1.66 NS | 0.27 NS | n=5, 7 NS | 84.1 |
| Available Cu (mg.kg$^{-1}$) | 1.45 | 1.25 | 16.0 | 1.19 NS | 8.38 ** | - | 10.9 |
| Soluble B (mg.kg$^{-1}$) | 0.183 | 0.261 | 42.6 | 0.37 NS | 3.10 NS | n=9, 8 * | 42.4 |
| Available B (mg.kg$^{-1}$) | 0.331 | 0.480 | 45.0 | 1.34 NS | 11.36 ** | - | 23.2 |
| Soluble Cl (mg.kg$^{-1}$) | 12.6 | 17.0 | 34.2 | 2.52 NS | 8.45 ** | - | 21.3 |

Notes:
[1]With respect to the smaller value
[2] F tests for Tr x Ty interaction and Ty factor in the AOV and Wilcoxon's test for n paired data of 9 subplots with T statistic value
[3]Not significant (NS) for p≥0,10 or significant for 0.10>p≥0.05 (*),0.05>p≥0.01 (**), or p<0.01 (***)
[4]Factors: Tr (soil treatments, in wholeplots) y Ty (soil types, in subplots)

The average concentration of easily oxidizable C in the Oyolopampa surface soil was 13.8 g.kg$^{-1}$. This is equivalent to about 3.1 % organic matter and can be considered as medium. This parameter had similar values in both soil types (Table 1). In a data meta-analysis, Liu et al. (2022) concluded that the total organic C content in rhizospheric soil usually was higher, by 9 % on average, than in bulk soil. Any change of the organic C content of the soil depended on the quantities of added and mineralized C. Sources of organic C in the rhizosphere were dead root residues and rhizodepositions. The latter included exudates, excretions, secretions, mucilage, and lysed root cells (Neumann & Ludewig, 2023). In a data meta-analysis, Ma et al. (2023) concluded that average organic C decomposition rates were 25 % higher in rhizospheric soil than in bulk soil. In this investigation, addition and mineralization of organic C apparently cancelled each other out.

The effective CEC of the studied soil had an average value of 13.9 cmol$_c$.kg$^{-1}$, classified as medium. This parameter had comparable levels in both soil types (Table 1). This could have been anticipated since a change in the concentration of surface-charge bearing minerals was not expected in the short term, the easily oxidizable C was similar, and the pH of the rhizospheric soil was only slightly different. Higher CEC values of rhizospheric soil compared to bulk soil have been reported in the literature (Chiu et al., 2002; Camps et al., 2003; Turpault et al., 2005). In these investigations, the concentration of total organic C was also larger in the rhizospheric soil.

The average pH of the Oyolopampa surface soil was 4.29, which can be considered as extremely acid. This parameter was slightly higher in rhizospheric soil than in bulk soil (Table 1). This difference was statistically significant in the AOV. Since the CVS was very small (<10 %), this discrepancy of 0.12 units did not seem to have real and practical importance. In other studies, pH values measured in rhizospheric soil were up to 2 units higher or lower than in bulk soil (Chiu et al., 2002; Camps et al., 2003; Liu et al., 2022; Neumann & Ludewig, 2023), being 0.16 units larger on average (Liu et al., 2022). These differences have been attributed to: (i) unequal absorption of cationic and anionic charge by roots, (ii) exudation of organic acids, (iii) release of $CO_2$ during aerobic respiration of soil organisms, (iv) redox reactions, and (v) adaptation mechanisms of roots subjected to nutrient deficiencies or toxic substances (Hinsinger et al., 2003; Neumann & Ludewig, 2023). Although any of these processes may have happened in this study, no net effect was observed.

The concentration of extractable acidity in the studied soil had an average value of 0.38 cmol$_c$.kg$^{-1}$. If this parameter comprised mainly exchangeable $Al^{3+}$, it would have represented only 2.7 % of the effective CEC in a soil with such a low pH value. A detailed investigation of

this issue is required. The extractable acidity was larger in bulk soil than in rhizospheric soil (Table 1). This difference was not statistically significant in the AOV, but the CVS was very high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were not consistent in the wholeplots of the experiment (Table 1). Thus, the exchangeable acidity of both soil types was interpreted as statistically comparable. In other investigations, it was observed that rhizospheric soil had larger, similar, or smaller concentrations of exchangeable acidity than bulk soil (Camps et al., 2003; Turpault et al., 2005).

The total concentration of dissolved substances in the soil solution was evaluated by the soil salinity. The average value of the electrical conductivity of the soil saturation extract in the Oyolopampa surface soil was 0.48 $dS.m^{-1}$. This parameter was clearly and significantly higher in rhizospheric soil than in bulk soil (Table 1). The accumulation of soluble salts close to the root surface has been previously documented (Riley & Barber, 1970). In some studies, the content of various solutes in the rhizosphere was high enough to cause the precipitation of solid phases (Neumann & Ludewig, 2023). In this investigation, the rhizospheric soil was not saline and no precipitated solids were observed. The accumulation of dissolved substances near the root surface indicated that their net transport towards the rhizoplane and/or their net release from soil minerals or organic matter exceeded their net absorption by roots. Individual solutes did not necessarily follow the same pattern.

The total concentration of N in the studied soil had an average value of 2.08 $g.kg^{-1}$, which can be classified as medium to high. No statistically significant differences were observed between both soil types (Table 1). In other investigations, it was reported that rhizospheric soil had larger, similar, or lower levels of this property than bulk soil (Chiu et al., 2002; Liu et al., 2022). In a data meta-analysis, Liu et al. (2022) concluded that total N was frequently higher, by 14 % on average, in the rhizosphere. Organic N was the main component of total N in the studied soil. Possible sources of organic N in the rhizosphere include rhizodeposition (Neumann & Ludewig, 2023) and biological $N_2$ fixation (Smercina et al., 2019; Hungria & Nogueira, 2023; Marschner, 2023). On the other hand, the priming effects caused by roots have been observed to increase noticeably the mineralization of organic N in the rhizosphere (Gan et al., 2022; Ma et al., 2023; Marschner, 2023). In our study, organic N additions by rhizodeposition and $N_2$ fixation and N losses by mineralization apparently had comparable magnitudes in the rhizosphere.

The concentrations of soluble $NO_3^-$-N and available $NH_4^+$-N in the Oyolopampa surface soil had average values of 6.53 and 19.6 $mg.kg^{-1}$, respectively. Both parameters were much bigger in rhizospheric soil than in bulk soil (Table 1). The difference for soluble $NO_3^-$-N was not significant in the AOV, but its CVS was very high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were not consistent in the wholeplots of the experiment (Table 1). Thus, the soluble $NO_3^-$-N of both soil types was interpreted as statistically comparable. In other investigations, it was observed that rhizospheric soil could have larger, similar, or smaller values of soluble $NO_3^-$-N than bulk soil (Turpault et al., 2005; Liu et al., 2022). In a data meta-analysis, Liu et al. (2022) concluded that the soluble $NO_3^-$-N frequently was larger, by 24 % on average, in the soil adjacent to root surfaces. The available $NH_4^+$-N was a bigger N pool than the soluble $NO_3^-$-N. The difference in available $NH_4^+$-N between both soil types was statistically significant in the AOV (Table 1). In the literature, it has been reported that rhizospheric soil could have higher, comparable, or lower values of available N than bulk soil, being 10 % higher on average (Liu et al., 2022). In a data meta-analysis, Ma et al. (2023) concluded that the N mineralization rate usually was higher in zones adjacent to roots, being the increase 27 % on average. Thus, the higher $NH_4^+$-N level observed in the rhizospheric soil of our study could be explained by a stimulated organic N mineralization. Thus, a parallel increase of soluble $NO_3^-$-N would have been expected.

The average concentrations of soluble and available P in the studied soil were 0.0283 and 34 $mg.kg^{-1}$, respectively. The available P level can be considered as very high. The soluble P concentration was much higher in rhizospheric soil than in bulk soil (Table 1). This difference was not significant in the AOV, but the CVS was

very high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were not consistent in the wholeplots of the experiment (Table 1). Thus, the soluble P of both soil types was interpreted as statistically comparable. In addition, the quality of the analytical data was not completely satisfactory, since the values for some extracts were below the detection level. In the literature, it was reported that rhizospheric soil had larger, similar, or smaller soluble P values than bulk soil (Camps et al., 2003; Turpault et al., 2005; Ye et al., 2018). In contrast, the available P content was similar in both soil types (Table 1). Given that the available P in this investigation had such a high value, it was not expected to change due to the corn root activity during a few months. In other investigations, it was noticed that rhizospheric soil could have higher, comparable, or lower available P values than bulk soil (Ye et al., 2018; Liu et al., 2022). In a data meta-analysis, Liu et al. (2022) concluded that the available P was commonly smaller, by 12 % on average, in the rhizosphere. The release of P within the rhizosphere may have occurred by biological dissolution of P bearing minerals (Spohn et al., 2020; Marschner, 2023), chemical dissolution of solids, desorption from solid surfaces, and/or mineralization of organic P by phosphatases (Ye et al., 2018; Marschner, 2023; Wang et al., 2023). Loss of P from the rhizosphere could have happened by adsorption on solid surfaces, root absorption, and/or microbial immobilization. In this study, the rates of P release and loss in the rhizosphere apparently matched each other.

The concentrations of soluble and available K in the Oyolopampa surface soil had average values of 8.34 $mg.kg^{-1}$ and 476 $mg.kg^{-1}$, respectively. Both parameters were greater in rhizospheric soil than in bulk soil, being less marked for available K (Table 2). The level of available K can be classified as high. In other studies, it was observed that rhizospheric soil had larger, similar, or smaller values of soluble K than bulk soil (Camps et al., 2003; Moritsuka et al., 2004; Turpault et al., 2005; Hinsinger et al., 2021). In the literature, it was also reported that rhizospheric soil could have higher, comparable, or lower values of available K than bulk soil (Chiu et al., 2002; Camps et al., 2003; Moritsuka et al., 2004; Turpault et al., 2005; Liu et al., 2022). In a data meta-analysis, Liu et al. (2022) concluded that the available K was commonly higher, by 15 % on average, in the rhizosphere. Accumulation of K within the rhizosphere may have happened via mass flow of soluble K towards the root surface. In addition, K buildup in rhizospheric soil could have occurred by dissolution of K bearing minerals. This might have been induced by low K concentration in the soil solution close to the rhizoplane, exudation of organic compounds and acidification by plant roots, and/or microbial activity (Moritsuka et al., 2004; Raghavendra et al., 2016; Hinsinger et al., 2021).

The average concentrations of soluble and available Ca in the studied soil were 17.6 and 1929 $mg.kg^{-1}$, respectively. The level of available Ca can be considered as medium. No significant differences between rhizospheric and bulk soil values were observed for both parameters (Table 2). In other studies, it was reported that rhizospheric soil had higher, similar, or lower levels of soluble Ca than bulk soil (Barber & Ozanne, 1970; Camps et al., 2003; Turpault et al., 2005). In some investigations, the soluble Ca level in rhizospheric soil was high enough to cause the precipitation of calcite and gypsum (Neumann & Ludewig, 2023). This was not observed in this study. The available Ca was a much bigger and more stable nutrient pool than soluble Ca. In the literature, it was observed that rhizospheric soil could have larger, similar, or smaller values of available Ca than bulk soil (Chiu et al., 2002; Camps et al., 2003; Turpault et al., 2005). In this study, Ca was apparently absorbed by plant roots at a rate that was similar to its supply by mass flow and/or its release within the rhizosphere.

The concentrations of soluble and available Mg in the Oyolopampa surface soil had average values of 3.66 $mg.kg^{-1}$ and 296 $mg.kg^{-1}$, respectively. The available Mg level can be classified as medium. The values of both parameters were higher in rhizospheric soil than in bulk soil (Table 2). However, only the difference for soluble Mg was significant in the AOV. It has been previously documented that rhizospheric soil could have higher or lower levels of soluble Mg than bulk soil (Camps et al.,

2003; Turpault et al., 2005). The available Mg pool was much bigger than that of soluble Mg and had a higher stability. Thus, both soil types had similar available Mg levels in the present study (Table 2). In other investigations, it was reported that rhizospheric soil could have similar or larger levels of this parameter than bulk soil (Chiu et al., 2002; Camps et al., 2003; Turpault et al., 2005). In this study, corn roots seem to have extracted Mg at a lower rate than its addition by mass flow and/or its release within the rhizosphere.

The average concentrations of soluble and available $SO_4^{2-}$-S in the studied soil were 1.53 and 45.1 mg.kg$^{-1}$, respectively. The available S level may tentatively be considered as medium to high. The concentration of soluble S in bulk soil was markedly higher than in rhizospheric soil (Table 2). This difference was not significant in the AOV, but the CVS was very high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were not consistent in the wholeplots of the experiment (Table 2). Thus, the soluble S content of both soil types was interpreted as statistically comparable. In other studies, it was observed that rhizospheric had similar or higher soluble S values than bulk soil (Camps et al., 2003; Turpault et al., 2005). The available S level of rhizospheric and bulk soils were similar in this investigation (Table 2). In another study, it was reported that rhizospheric soil could have similar or higher concentrations of available S than bulk soil (Hu et al., 2003). In the present investigation, S was apparently absorbed by corn roots at a similar rate than that of its supply by mass flow and/or its release by mineralization of organic S or desorption from solid surfaces within the rhizosphere.

The concentrations of soluble and available Fe in the Oyolopampa surface soil had average values of 0.0265 and 357 mg.kg$^{-1}$, respectively. The available Fe level may be classified as medium. No significant difference between rhizospheric and bulk soil values were observed for both parameters (Table 2). In other studies, rhizospheric soils had higher or lower levels of soluble Fe and larger, comparable, or smaller concentrations of available Fe than bulk soil (Youssef & Chino, 1989; Turpault et al., 2005). In the present investigation, Fe seemed to be absorbed by corn roots at a rate that was comparable with that of its release by dissolution of Fe bearing minerals and/or desorption from solid surfaces within the rhizosphere.

The average concentrations of soluble and available Mn in the studied soils were 0.435 and 198 mg.kg$^{-1}$, respectively. The level of available Mn may be considered as high. The concentration of soluble Mn was higher in rhizospheric soil than in bulk soil (Table 3). This difference was not significant in the AOV, but the CVS was very high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were not consistent in the wholeplots of the experiment (Table 3). Thus, the soluble Mn of both soil types was interpreted as statistically comparable. In other investigations, it was observed that rhizospheric soil had higher values of soluble Mn than bulk soil (Youssef & Chino, 1989; Turpault et al., 2005). The concentration of available Mn was significantly greater in rhizospheric soil than in bulk soil (Table 3). This was consistent with the results of several investigations (Youssef & Chino, 1989; Turpault et al., 2005). However, its CVS was very small (<10 %). Thus, the difference in available Mn between both soil types was interpreted as not important in this investigation. Rhizospheric soil can also have lower levels of available Mn than bulk soil (Kothari et al., 1991). In this study, Mn was apparently extracted by corn roots at a similar rate than that of its release by dissolution of Mn bearing solids and/or desorption from solid surfaces within the rhizosphere.

The concentrations of soluble and available Zn in the Oyolopampa surface soil had average values of 0.131 and 3.28 mg.kg$^{-1}$, respectively. The available Zn level can be classified as medium. The soluble Zn level in rhizospheric soil was lower than in bulk soil (Table 3). This difference was not significant in the AOV, but the CVS was high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were not consistent in the wholeplots of the experiment (Table 3). Thus, the soluble Zn content of both soil types was interpreted as statistically comparable. In the literature, it was reported that rhizospheric soil had larger, similar, or smaller concentrations of soluble Zn than

bulk soil (Youssef & Chino, 1989; Courchesne et al., 2009). The available Zn had similar values in both soil types (Table 3). In other studies, it was observed that rhizospheric soil had higher, comparable, or lower values of available Zn than bulk soil (Youssef & Chino, 1989; Courchesne et al., 2009). In this investigation, Zn seemed to be absorbed by corn roots at a similar rate than that of its release in the rhizosphere by dissolution of Zn bearing minerals and/or desorption from the solid surfaces.

The average concentrations of soluble and available Cu in the studied soil were 0.0029 and 1.35 $mg.kg^{-1}$, respectively. The level of available Cu can be considered as medium to low. Both parameters had lower values in rhizospheric soil than in bulk soil (Table 3). The difference for soluble Cu was not significant in the AOV, but its CVS was very high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were not consistent in the wholeplots of the experiment (Table 3). Thus, the soluble Cu content of both soil types was interpreted as statistically comparable. Furthermore, the quality of the analytical data was not entirely satisfactory since Cu could not be detected in several soil extracts. In other studies, it was reported that rhizospheric soil had larger, similar, or smaller values of soluble Cu than bulk soil (Youssef & Chino, 1989, Courchesne et al., 2009). The difference of available Cu between both soil types was significant in the AOV (Table 3). In the literature, it was observed that rhizosphere soil had higher, comparable, or lower values of available Cu than bulk soil (Youssef & Chino, 1989; Courchesne et al., 2009). In this study, corn roots apparently extracted Cu at relatively high rate, and the available Cu pool got smaller. This rate obviously was larger than that of Cu release in the rhizosphere by dissolution of Cu bearing minerals and/or desorption from solid surfaces.

The concentrations of soluble and available B in the Oyolopampa surface soil had average values of 0.222 and 0.406 $mg.kg^{-1}$, respectively. The level of available B can be classified as medium. Both parameters were markedly larger in rhizospheric soil than in bulk soil (Table 3). The difference for soluble B was not significant in the AOV, but its CVS was high (>35 %). The Wilcoxon test indicated that the discrepancies between both soil types were consistent in the wholeplots of the experiment (Table 3). Thus, the soluble B content was interpreted as statistically greater in rhizospheric soil than in bulk soil. On the other hand, the difference for available B was significant in the AOV (Table 3). In another investigation, it was reported that rhizospheric soil could have larger, similar, or smaller levels of available B than bulk soil (Mandal et al., 2012). In this study, corn roots apparently absorbed B at a smaller rate than that of its supply by mass flow towards the rhizoplane and/or its release by dissolution of B bearing minerals or desorption from solid surfaces within the rhizospheric soil.

The average concentration of soluble Cl ($Cl^-$) in the studied soil was to 14.8 $mg.kg^{-1}$. This parameter was significantly larger in rhizospheric soil than in bulk soil (Table 3). It has been stated that $Cl^-$ tends to accumulate in the rhizosphere because its concentration in the soil solution is relatively high, its transport towards the rhizoplane by mass flow is high and continuous, and it is not extracted in high amounts by plant roots (Neumann & Ludewig, 2023). This is consistent with our results and with those of other studies (Camps et al., 2003; Turpault et al., 2005). Soluble and available Cl can be considered as equivalent.

In the Oyolopampa surface soil, only 9 of the 29 evaluated chemical properties showed important differences between rhizospheric and bulk soils, according to our interpretation criteria. The only basic chemical soil property within this group was salinity. This parameter seemed to be more variable than other basic properties by the processes that occur in the rhizosphere, since it was mainly a side effect of the water absorption by plant roots. Among the 24 nutrient availability indexes, 8 had different values in both soil types. These included available $NH_4^+$-N, soluble and available K, soluble Mg, available Cu, soluble and available B, and soluble Cl. Soluble Cl had the same behavior as soil salinity. Complete explanations of these and other observations require more detailed information about the system and transcend the objectives of this study. The soluble fraction of the mineral elements was expected to be different between rhizospheric and bulk soils, since it was a much smaller nutrient pool and was expected

to easily change. Nevertheless, only 4 (K, Mg, B, and Cl) of the 12 studied essential elements showed this behavior. On the other hand, the more stable available nutrient pool was similar in both soil types for the majority of the evaluated nutrient elements, including P, Ca, Mg, S, Fe, Mn, and Zn. Furthermore, the differences between rhizospheric and bulk soils may have been clouded by the much higher variability of the soluble fraction of some elements (Tables 1 to 3). Our results and the cited literature showed that the differences between both soil types did not follow a repetitive pattern, with the possible exceptions of soil salinity and soluble Cl content. The remaining chemical properties were larger, similar, or smaller in the rhizospheric soil, depending on the specific situation that was examined. These case-specific outcomes depended on the evaluated property or substance, plant genotype, soil properties, local environmental conditions, and moment of examination.

The values of the chemical properties of the rhizospheric soil in a specific case are due to the variety and complexity of the processes that occur in it. A mass balance analysis can be constructed for a given mineral nutrient (soluble or available) or other substance of interest. The variables in this analysis are: net accumulation of the substance in the rhizosphere (A), its net amount entering the rhizosphere from zones that are away from the root surface (I), its net release within the rhizosphere (R), and its net rhizodeposition into the rhizosphere (D). The mass balance equation is: A = I + R + D. Each variable may be positive, 0, or negative. A positive value implies accumulation of the substance in the rhizosphere. Variable I can be described by mass flow (>0 or 0) and/or diffusion (>0, 0, or <0) transport processes. Variable R (>0, 0, or <0) is given by chemical and biological processes. Chemical rhizosphere processes include dissolution-precipitation of solids, desorption-adsorption on soil solid surfaces, formation-decomposition through reactions in solution, and dissolution-volatilization of gases. Biological processes that occur in the rhizosphere comprise mineralization-immobilization, biological fixation-volatilization, and other biochemical processes. Variable D is assessed from the absorption of the substance by plant roots (<0) and its rhizodeposition (>0 or 0). In addition, special processes carried out by the rhizospheric biota (exudation of organic acids, acidification, etc.) must also be considered. It must be noted that these processes tend to influence each other. Finally, these processes depend on chemical nature of the substance, plant genotype, soil type, local environment, and moment in time. The net result of all these processes will ultimately establish if the rhizosphere is going to be enriched with or depleted of this substance. In addition, the outcome for a group of substances should be highly variable, complex, and case-specific.

Within the last 60 years, mathematical models have been developed to describe and predict the properties and behavior of the rhizosphere (Kuppe et al., 2022). These models were typically based on mass balance analysis and relevant rhizosphere processes. The use of these models usually requires many details of the system, and its operation is not always easy. Tools like these may eventually and help us understand and predict the specific and complex observations reported in this study and other investigations.

## Conclusions

The rhizospheric soil in the Oyolopampa corn field differed from the bulk soil in 31 % of the 29 evaluated chemical properties. Salinity was the only basic chemical parameter in this group and it was higher in the rhizospheric soil. Among nutrient availability indexes, available $NH_4^+$-N, soluble and available K, soluble Mg, soluble and available B, and soluble Cl where larger in the rhizospheric soil, while available Cu was higher in the bulk soil. Soluble concentrations of only 4 of the 12 studied nutrient elements differed between both soil types. In contrast, the available contents of most mineral nutrients were similar in rhizospheric and bulk soils.

Our results and literature survey showed that the chemical properties of the rhizospheric soil could have larger, similar, or smaller values than the bulk soil, with the possible exceptions of salinity and soluble Cl content. Thus, the differences between these soil types were case-specific and depended on the evaluated property or substance, plant genotype, soil properties, environmental conditions, and moment of examination.

## Acknowledgments

Comunidad of Oyolopampa (Páucar del Sara Sara, Ayacucho, Peru) for helping to carry out the field experiment and for support during soil sampling. Special thanks are extended to Martín Calderón, Isabel Quispe, Alberto Condori, Erasmo Martínez and Constantina Calderón.

Laboratorio de Análisis de Suelos, Plantas, Aguas y Fertilizantes (LASPAF) of the Faculty of Agronomy of the Universidad Nacional Agraria La Molina for carrying out chemical analysis of the soil samples and covering the related expenses.

## Author contributions

KPRW: Design of laboratory experiment, analysis and interpretation of results, and manuscript preparation.

CSCM: Design y conduction of field experiment, collection of soil samples, and manuscript proofing.

## Conflict of interest

There is no conflict of interest.

## Funding declaration

This work did not receive any funding in the form of a grant.

## ID ORCID and e-mails

Raven, K. kpraven@lamolina.edu.pe
https://orcid.org/0009-0001-8533-8910

Calderón, C. ccalderon@lamolina.edu.pe
https://orcid.org/0000-0002-4289-2110

## References

Adamczewski, R., Kaestner, A., & Zarebanadkouki, M. (2024). Rhizosphere hydraulic regulation in maize: tailoring rhizosphere properties to varying soil textures and moistures. *Plant Soil, 509,* 53–66. https://doi.org/10.1007/s11104-024-06840-2

Ahkami, A. H., White, R. A., Handakumbura, P. P., & Jansson, C. (2017). Rhizosphere engineering: Enhancing sustainable plant ecosystem productivity. *Rhizosphere, 3*, 233–243. https://doi.org/10.1016/j.rhisph.2017.04.012

Barber, S. A., & Ozanne, P. G. (1970). Autoradiographic evidence for the differential effect of four plant species in altering the calcium content of the rhizosphere soil. *Soil Science Society of America Journal, 34*(4), 635–637. https://doi.org/10.2136/sssaj1970.03615995003400040027x

Bazán T., R. (1996). *Manual de análisis químico de suelos, aguas y plantas*. Universidad Nacional Agraria La Molina - Fundación Perú, Lima, Perú.

Camps, A. M., Barreal, M. E., Mourenza, C., Álvarez, E., Kidd, P., & Macías, F. (2003). Rhizosphere chemistry in acid forest soils that differ in their degree of Al-saturation of organic matter. *Soil Science, 168*(4), 267–279. https://doi.org/10.1097/01.ss.0000064890.94869.a8

Chiu, C. Y., Wang, M. K., Hwong, J. L., & King, H. B. (2002). Physical and chemical properties in rhizosphere and bulk soils of Tsuga and Yushania in a temperate rain forest. *Communications in Soil Science and Plant Analysis, 33*(11–12), 1723–1735. https://doi.org/10.1081/CSS-120004818

Courchesne, F., Kruyts, N., & Legrand, P. (2009). Labile zinc concentration and free copper ion activity in the rhizosphere of forest soils. *Environmental Toxicology and Chemistry, 25*(3), 635–642. https://doi.org/10.1897/04-593R.1

Dessaux, Y., Grandclément, C., & Faure, D. (2016). Engineering the rhizosphere. *Trends in Plant Science, 21*(3), 266–278. https://doi.org/10.1016/j.tplants.2016.01.002

Gan, D., Zeng, H., & Zhu, B. (2022). The rhizosphere effect on soil gross nitrogen mineralization: A meta-analysis. *Soil Ecology Letters, 4*(2), 144–154. https://doi.org/10.1007/s42832-021-0098-y

Helliwell, J. R., Sturrock, C. J., Miller, A. J.,

Whalley, W. R., & Mooney, S. J. (2019). The role of plant species and soil condition in the structural development of the rhizosphere. *Plant, Cell & Environment, 42*(6), 1974–1986. https://doi.org/10.1111/pce.13529

Hinsinger, P., Bell, M. J., Kovar, J. L., & White, P. J. (2021). Rhizosphere processes and root traits determining the acquisition of soil potassium. In T. S. Murrell, R. L. Mikkelsen, G. Sulewski, R. Norton & M. L. Thompson (Eds.), *Improving potassium recommendations for agricultural crops* (99–117). Springer. https://doi.org/10.1007/978-3-030-59197-7_4

Hinsinger, P., Plassard, C., Tang, C., & Jaillard, B. (2003). Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: A review. *Plant and Soil, 248*(1-2), 43–59. https://doi.org/10.1023/A:1022371130939

Hu, Z., Haneklaus, S., Wang, S., Xu, C., Cao, Z., & Schnug, E. (2003). Comparison of mineralization and distribution of soil sulfur fractions in the rhizosphere of oilseed rape and rice. *Communications in Soil Science and Plant Analysis, 34*(15–16), 2243–2257. https://doi.org/10.1081/CSS-120024061

Hungria, M., & Nogueira, M. A. (2023). Nitrogen fixation. In Z. Rengel, I. Cakmak & P. J. White (Eds.), *Marschner's mineral nutrition of plants*. Academic Press. (4th ed., pp. 615–650). https://doi.org/10.1016/B978-0-12-819773-8.00006-X

Kothari, S. K., Marschner, H., & Römheld, V. (1991). Effect of a vesicular-arbuscular mycorrhizal fungus and rhizosphere micro-organisms on manganese reduction in the rhizosphere and manganese concentrations in maize (*Zea mays* L.). *New Phytologist, 117*(4), 649–655. https://doi.org/10.1111/j.1469-8137.1991.tb00969.x

Kuppe, C. W., Schnepf, A., von Lieres, E., Watt, M., & Postma, J. A. (2022). Rhizosphere models: Their concepts and application to plant-soil ecosystems. *Plant and Soil, 474*, 17-55. https://doi.org/10.1007/s11104-021-05201-7

Ling, N., Wang, T., & Kuzyakov, Y. (2022). Rhizosphere bacteriome structure and functions. *Nature Communications, 13*(836). https://doi.org/10.1038/s41467-022-28448-9

Liu, S., He, F., Kuzyakov, Y., Xiao, H., Hoang, D. T. T., Pu, S., & Razavi, B. S. (2022). Nutrients in the rhizosphere: A meta-analysis of content, availability, and influencing factors. *Science of the Total Environment, 826*, 153908. https://doi.org/10.1016/j.scitotenv.2022.153908

Ma, Y., Yue, K., Heděnec, P., Li, C., Li, Y., & Wu, Q. (2023). Global patterns of rhizosphere effects on soil carbon and nitrogen biogeochemical processes. *Catena, 220*, 106661. https://doi.org/10.1016/j.catena.2022.106661

Mandal, M., Das, D. K., & Mazumdar, D. (2012). Evaluation of extractants for boron under the influence of organic matter and applied boron in rhizosphere and nonrhizosphere soils growing rape (*Brassica campestris* L.). *Communications in Soil Science and Plant Analysis, 43*(6), 973–983. https://doi.org/10.1080/00103624.2012.653295

Marschner, P. (2023). Rhizosphere biology. In Z. Rengel, I. Cakmak & P. J. White (Eds.), *Marschner's mineral nutrition of plants* (4th ed., pp. 587–614). Academic Press. https://doi.org/10.1016/B978-0-12-819773-8.00004-6

Moritsuka, N., Yanai, J., & Kosaki, T. (2004). Possible processes releasing nonexchangeable potassium from the rhizosphere of maize. *Plant and Soil, 258*(1), 261–268. https://doi.org/10.1023/B:PLSO.0000016556.79278.7f

Neumann, G., & Ludewig, U. (2023). Rhizosphere chemistry influencing plant nutrition. In Z. Rengel, I. Cakmak & P. J. White (Eds.), *Marschner's mineral nutrition of plants* (4th ed., pp. 545–585). Academic Press. https://doi.org/10.1016/B978-0-12-819773-8.00013-7

Ott, L., & Longnecker, M. (2016). *An introduction to statistical methods & data analysis* (7th ed.). Cengage Learning.

Pantigoso, H. A., Newberger, D., & Vivanco, J. M. (2022). The rhizosphere microbiome: Plant-microbial interactions for resource acquisition. *Journal of Applied Microbiology, 133*(5), 2864–2876. https://doi.org/10.1111/jam.15686

Raghavendra, M. P., Chandra Nayaka, S., Nuthan, B. R. (2016). Role of rhizosphere microflora in potassium solubilization. In: Meena, V., Maurya, B., Verma, J., & Meena, R. (Eds.), *Potassium solubilizing microorganisms for sustainable agriculture* (pp. 43–59). Springer, New Delhi. https://doi.org/10.1007/978-81-322-2776-2_4

Riley, D., & Barber, S. A. (1970). Salt accumulation at the soybean (*Glycine max* (L.) Merr.) root-soil interface. *Soil Science Society of America Journal, 34*(1), 154–155. https://doi.org/10.2136/sssaj1970.03615995003400010042x

Schnepf, A., Carminati, A., Ahmed, M. A., Ani, M., Benard, P., Bentz, J., Bonkowski, M., Knott, M., Diehl, D., Duddek, P., Kröner, E., Javaux, M., Landl, M., Lehndorff, E., Lippold, E., Lieu, A., Mueller, C. W., Oburger, E., Otten, W., Portell, X., Phalempin, M., Prechtel, A., Schulz, R., Vanderborgth, J., & Vetterlein, D. (2022). Linking rhizosphere processes across scales: Opinion. *Plant and Soil*, 478, 5–42. https://doi.org/10.1007/s11104-022-05306-7

Smercina, D. N., Evans, S. E., Friesen, M. L., & Tiemann, L. K. (2019). To fix or not to fix: Controls on free-living nitrogen fixation in the rhizosphere. *Applied and Environmental Microbiology, 85*(6), e2546-18. https://doi.org/10.1128/AEM.02546-18

Spohn, M., Zeißig, I., Brucker, E., Widdig, M., Lacher, U., & Aburto, F. (2020). Phosphorus solubilization in the rhizosphere in two saprolites with contrasting phosphorus fractions. *Geoderma, 366*, 114245. https://doi.org/10.1016/j.geoderma.2020.114245.

Solomon, W., Janda, T., & Molnár, Z. (2024). Unveiling the significance of rhizosphere: Implications for plant growth, stress response, and sustainable agriculture. Plant *Physiology and Biochemistry, 206*. https://doi.org/10.1016/j.plaphy.2023.108290

Thakur, M., Khushboo, Shah, S., Kumari, P., Kumar, M., Vibhuti, R. K., Pramanik, A., Yadav, V., Raina, M., Negi, N. P., Gautam, V., Rustagi, A., Verma, S. K., & Kumar, D. (2024). Unlocking the secrets of rhizosphere microbes: A new dimension for agriculture. *Symbiosis 92*, 305–322. https://doi.org/10.1007/s13199-024-00980-w

Turpault, M.-P., Utérano, C., Boudot, J.-P., & Ranger, J. (2005). Influence of mature Douglas fir roots on the solid soil phase of the rhizosphere and its solution chemistry. *Plant and Soil, 275*(1–2), 327–336. https://doi.org/10.1007/s11104-005-2584-x

Wang, L., Rengel, Z., Zhang, K., Jin, K., Lyu, Y., Zhang, L., Cheng, L., Zhang, F., & Shen, J. (2022). Ensuring future food security and resource sustainability: Insights into the rhizosphere. *iScience, 25*(4), 104168. https://doi.org/10.1016/j.isci.2022.104168

Wang, Y., Luo, D., Xiong, Z., Wang, Z., & Gao, M. (2023). Changes in rhizosphere phosphorus fractions and phosphate-mineralizing microbial populations in acid soil as influenced by organic acid exudation. *Soil & Tillage Research, 225*, 105543. https://doi.org/10.1016/j.still.2022.105543

Ye, D., Zhang, X., Li, T., Xu, J., & Chen, G. (2018). Phosphorus-acquisition characteristics and rhizosphere properties of wild barley in relation to genotypic differences as dependent on soil phosphorus availability. *Plant and Soil, 423*(1–2), 503–516. https://doi.org/10.1007/s11104-017-3530-4

York, L. M., Carminati, A., Mooney, S. J., Ritz, K., & Bennett, M. J. (2016). The holistic rhizosphere: Integrating zones, processes, and semantics in the soil influenced by roots. *Journal of Experimental Botany, 67*(12),

3629–3643. https://doi.org/10.1093/jxb/erw108

Youssef, R. A., & Chino, M. (1989). Root-induced changes in the rhizosphere of plants. II. Distribution of heavy metals across the rhizosphere in soils. *Soil Science and Plant Nutrition, 35*(4), 609–621. https://doi.org/10.1080/00380768.1989.10434796