NICKEL IMPACT ON THE SOIL BIOLOGICAL AND FUNCTIONAL PROPERTIES

IMPACTO DO NÍQUEL NAS PROPRIEDADES BIOLÓGICAS E FUNCIONAIS DO SOLO

IMPACTO DEL NÍQUEL EN LAS PROPIEDADES BIOLÓGICAS Y FUNCIONALES DEL SUELO

https://doi.org/10.56238/sevened2025.016-005

Gabriel Maurício Peruca de Melo[1], Liandra Maria Abaker Bertipaglia[2], Wanderley José de Melo[3], Reginaldo Ribeiro dos Santos[4], Jorge Manussakis Barbosa[5], Rodrigo de Mello Lima Othon[6], Vito Antonio Merlino Junior[7], Gabriel Silva Bariotto[8], Pedro Vinicius Damaceno[9]

ABSTRACT
This chapter addresses the effects of nickel (Ni) on soil biological properties, with an emphasis on microbial biomass, enzymatic activity, and basal respiration. Although nickel is a micronutrient, its accumulation in agricultural soils—often resulting from anthropogenic activities—can impair soil microbiota by inhibiting enzymes and altering nutrient cycling and the carbon cycle. Microbial biomass and basal respiration are sensitive indicators of Ni levels, showing significant reductions at high metal concentrations, while low doses may have beneficial effects. Enzymatic activity is also directly inhibited, particularly enzymes such as dehydrogenase and urease. Factors such as organic matter content, pH, soil texture, and the presence of soil organisms influence the magnitude of these effects. Strategies such as the addition of organic matter, the use of Ni-hyperaccumulating plants, and conservation management practices are highlighted as alternatives to mitigate nickel toxicity. The chapter emphasizes the importance of monitoring the effects of Ni on soil biology and proposes the use of microbiological attributes as tools for environmental diagnostics.

Keywords: Microbial Biomass. Enzymatic Activity. Basal Respiration. Soil Microbiota. Environmental Diagnostics. Mitigation Strategies.

RESUMO
Este capítulo aborda os efeitos do níquel (Ni) sobre as propriedades biológicas do solo, com ênfase na biomassa microbiana, atividade enzimática e respiração basal. Embora o níquel seja um micronutriente, seu acúmulo em solos agrícolas — frequentemente resultante de

[1] Dr. Faculdade de Ciências Agrárias e Veterinárias (FCAV-UNESP). Titular at Universidade Brasil. E-mail: gabriel.melo@ub.edu.br
[2] Dr. Faculdade de Ciências Agrárias e Veterinárias (FCAV-UNESP). Titular at Universidade Brasil. E-mail: liandra.bertipaglia@ub.edu.br
[3]Dr. Escola Superior de Agricultura Luiz de Queiroz da Universidade de São Paulo (ESALQ-USP). E-mail: wanderley.melo@ub.edu.br
[4]Master in Animal Production. Universidade Brasil (UB). E-mail: reginaudo@gmail.com
[5] Master in Animal Production. Universidade Brasil (UB). E-mail: jorge.jomaba@gmail.com
[6] Master in Animal Production. Universidade Brasil (UB). E-mail: rodrigoothon.21@gmail.com
[7]Bachelor's Degree in Agronomy. Universidade Brasil (UB). E-mail: vitoamerlino28@hotmail.com
[8] Bachelor's Degree in Agronomy. Universidade Brasil (UB). E-mail: gabrielbariotto12@outlook.com
[9] Bachelor's Degree in Agronomy. Universidade Brasil (UB). E-mail: pedrodamaceno019@gmail.com

atividades antrópicas — pode prejudicar a microbiota do solo ao inibir enzimas e alterar o ciclo de nutrientes e o ciclo do carbono. A biomassa microbiana e a respiração basal são indicadores sensíveis aos níveis de Ni, apresentando reduções significativas em concentrações elevadas do metal, enquanto doses baixas podem ter efeitos benéficos. A atividade enzimática também é diretamente inibida, especialmente enzimas como a desidrogenase e a urease. Fatores como o teor de matéria orgânica, pH, textura do solo e a presença de organismos edáficos influenciam a magnitude desses efeitos. Estratégias como a adição de matéria orgânica, o uso de plantas hiperacumuladoras de Ni e práticas de manejo conservacionistas são destacadas como alternativas para mitigar a toxicidade do níquel. O capítulo enfatiza a importância de monitorar os efeitos do Ni sobre a biologia do solo e propõe o uso de atributos microbiológicos como ferramentas de diagnóstico ambiental.

Palavras-chave: Biomassa Microbiana. Atividade Enzimática. Respiração Basal. Microbiota do Solo. Diagnóstico Ambiental. Estratégias de Mitigação.

RESUMEN

Este capítulo aborda los efectos del níquel (Ni) en las propiedades biológicas del suelo, con énfasis en la biomasa microbiana, la actividad enzimática y la respiración basal. Aunque el níquel es un micronutriente, su acumulación en suelos agrícolas (a menudo como resultado de actividades humanas) puede dañar la microbiota del suelo al inhibir las enzimas y alterar el ciclo de los nutrientes y el carbono. La biomasa microbiana y la respiración basal son indicadores sensibles de los niveles de Ni, mostrando reducciones significativas en altas concentraciones del metal, mientras que dosis bajas pueden tener efectos beneficiosos. También se inhibe directamente la actividad enzimática, especialmente enzimas como la deshidrogenasa y la ureasa. Factores como el contenido de materia orgánica, el pH, la textura del suelo y la presencia de organismos del suelo influyen en la magnitud de estos efectos. Se destacan estrategias como la adición de materia orgánica, el uso de plantas hiperacumuladoras de Ni y prácticas de manejo conservacionista como alternativas para mitigar la toxicidad del níquel. El capítulo enfatiza la importancia de monitorear los efectos del Ni en la biología del suelo y propone el uso de atributos microbiológicos como herramientas de diagnóstico ambiental.

Palabras clave: Biomasa Microbiana. Actividad Enzimática. Respiración Basal. Microbiota del Suelo. Diagnóstico Ambiental. Estrategias de Mitigación.

1 INTRODUCTION

The biological activity of soil results from the set of processes carried out by living organisms present in the soil environment. This activity is fundamental for fertility, nutrients, carbon cycling and the maintenance of soil quality. It is primarily driven by microorganisms, soil fauna, and enzymes, which interact to transform organic residues that reach the soil, leading to the release of nutrients and the formation of soil structure.

Among the main components of biological activity are microorganisms such as bacteria, fungi, protozoa, and actinomycetes, which play essential roles in the transformation of organic substances, mineralizing it and releasing nutrients while forming humic substances (Nannipieri et al., 2017; Tecon & Or, 2017; Trus et al., 2021; Kurmanbayev et al., 2023). Soil fauna, composed of earthworms, mites, nematodes, and other small animals, also contribute to biological activity by promoting aeration, mixing, and fragmentation of organic material (Trus et al., 2021; Kurmanbayev et al., 2023).

Other components of soil biological activity are enzymes such as β-glucosidase, phosphatase, urease, arylsulfatase, cellulase, and dehydrogenase, which catalyze essential reactions for the cycling of carbon, nitrogen, phosphorus, and sulfur. These are considered important indicators of biological activity (Adetunji et al., 2017; Levakov et al., 2021; Barbosa et al., 2023).

Several factors affect the magnitude and expression of soil biological activity. One of the most commonly used indicators is microbial biomass (SNB), which represents the amount of living microorganisms and is directly associated with the mineralization of organic residues (Barbosa et al., 2023; Kurmanbayev et al., 2023; Memoli et al., 2018). Organic matter, in turn, plays an essential role as a source of energy and nutrients, strongly influencing both microbial and enzymatic activity (Memoli et al., 2018; Trus et al., 2021; Barbosa et al., 2023).

Soil enzymatic activity has been widely used as an indicator of soil quality and as a tool to assess the effects of different land uses and management practices (Adetunji et al., 2017; Levakov et al., 2021; Barbosa et al., 2023; Kurmanbayev et al., 2023). Additionally, abiotic factors such as pH, soil texture, clay content, nutrient availability, and the presence of potentially toxic trace elements (PTTE) influence the composition and dynamics of the microbial community (Barbosa et al., 2023; Memoli et al., 2018).

The ecological functions performed by biological activity are broad and include 1) nutrient cycling by transforming organic residues into forms assimilable by plants (Adetunji et al., 2017; Trus et al., 2021; Kurmanbayev et al., 2023); 2) the formation and stability of soil structure, with direct impacts on water retention, erosion resistance, and nutrient-holding capacity (Trus et al., 2021; Tecon & Or, 2017); 2) its role as an indicator of environmental quality since high levels of biological activity are directly associated with productive and sustainable soils (Adetunji et al., 2017; Barbosa et al., 2023; Kurmanbayev et al., 2023).

Nickel (Ni) is a PTTE commonly found in soil because it is part of minerals that are part of the composition of the original rock, but its concentration in the soil increases as a result of human activities. Although it is a micronutrient for plants in small amounts, at high concentrations it can be toxic to both plants and soil microbiota, directly affecting enzymatic activity and, consequently, soil health.

In the agricultural and environmental context, Ni has been extensively studied for its toxic effects. Research aiming to establish its role in plant nutrition has focused on elucidating Ni's role in the nitrogen cycle (Kutman et al., 2014; Alibakhshi & Khoshgoftarmanesh, 2015), particularly due to its connection with the enzyme urease, of which it is a part of the enzyme active site.

For plants, Ni is an essential element (Bai et al., 2006), but its accumulation in the environment can result in phytotoxicity, harming plant growth and development (Ahmad et al., 2009).

Nickel uptake by plants is influenced by various soil and plant factors. The main factors affecting Ni phytoavailability in soil include pH, redox potential, texture, mineral composition (particularly the content and types of clays and Fe, Al, and Mn oxides), soil profile characteristics, cation exchange capacity (CEC), organic matter, the presence of other trace elements, and other factors that influence microbial activity (Kabata-Pendias & Pendias, 2001).

The presence of nickel significantly impacts plant enzymatic activity, especially enzymes related to nitrogen metabolism and protection against oxidative stress. Nickel acts as a cofactor for enzymes such as urease, involved in urea hydrolysis, and superoxide dismutase, which helps eliminate free radicals. These enzymes are related to plant growth and development, and the proper presence of nickel is essential for their efficient functioning (Andrade, 2023).

In this sense, scientific research is crucial to help advance the understanding of nickel's effects in soil–plant systems, determine nutritional and toxic thresholds for different crops, and assess its effects on soil microbiota. It is also important to define the total and available levels of this element permitted in soil, which is key for creating regulations on the use of residues in agriculture such as sewage sludge, for example.

2 NICKEL IN SOIL AND ITS BIOLOGICAL EFFECTS

Enzymatic activity is a direct reflection of the presence and activity of the microbiota, both of which are essential for ecological processes and soil fertility. The relationship between them is influenced by environmental factors and soil properties, but microbial diversity and biomass are key determinants of the intensity and diversity of enzymatic activities (Table 1).

Soil chemical properties (carbon content, nutrients, pH) explain much of the variation in enzymatic activity, but microbial abundance and diversity also play an important role (Tan et al., 2021; Ren et al., 2021; Piotrowska-Długosz et al., 2022; Xiao et al., 2024).

Environmental factors such as temperature, moisture, and substrate availability affect both microbiota and enzymatic activity (Ren et al., 2021; Daunoras et al., 2024; Xiao et al., 2024). Changes in land use, climate, and agricultural practices alter microbial composition and, consequently, the enzymatic profile (Daunoras et al., 2024; Ren et al., 2021; Yudina et al., 2023).

Table 1

Main factors influencing the relationship between enzymatic activity and soil microbiota

Factor	**Relationship with Enzymatic Activity**	**Reference**
Microbial diversity	Increases enzymatic diversity	(Xing et al., 2024); Caldwell, 2005
Microbial biomass	Increases enzymatic activity	Frankenberger & Dick, 1983; (Piotrowska-Długosz et al., 2022)
Soil properties	Influence microbiota and enzymatic activity	(Tan et al., 2021); (Ren et al., 2021); (Xiao et al., 2024); (Piotrowska-Długosz et al., 2022)
Environmental factors	Modulate the relationship	(Daunoras et al., 2024); (Ren et al., 2021); (Xiao et al., 2024); (Yudina et al., 2023)

Soil enzymes are mainly secreted by microorganisms and play a central role in the decomposition of organic substances and in cycle of elements (carbon, nitrogen, phosphorus, sulfur, and others) (Caldwell, 2005; Wang et al., 2023; Daunoras et al., 2024).

The activity of enzymes such as phosphatases, glucosidases, and dehydrogenases is strongly correlated with microbial respiration, microbial biomass, and microbial community diversity (Frankenberger & Dick, 1983; Caldwell, 2005; Xing et al., 2024). Enzymatic activity profiles can indicate the diversity and complexity of the microbial community, reflect the structure and function of decomposition and biosynthesis processes in the soil (Caldwell, 2005; Xing et al., 2024).

Dehydrogenase is often used as an indicator of overall microbiological activity and soil quality, as it reflects the ability of microorganisms to perform essential metabolic processes. Studies have shown that nickel contamination significantly reduces dehydrogenase activity. Trace elements and their compounds generally reduce soil enzymatic activity significantly (Nowak et al., 2000).

Urease, dehydrogenase, and phosphatases are sensitive to nickel, and are recommended as bioindicators of its contamination (Wyszkowska et al., 2018; Liu et al., 2018; Boros-Lajszner et al., 2017; Kucharski et al., 2009; CAI ET AL., 2005).

Most studies show that nickel contaminated soils exhibit significantly reduced activity of urease, dehydrogenase, acid and alkaline phosphatases, arylsulfatase, and β-glucosidase. The degree of inhibition depends on the nickel dose, being more pronounced at high concentrations (Helaoui et al., 2020; Wyszkowska et al., 2018; Liu et al., 2018; (Boros-Lajszner et al., 2017; Kucharski et al., 2009; CAI ET AL., 2005).

Wyszkowska et al. (2018) investigated the effects of different nickel concentrations (100, 200, 300, and 400 mg Ni/kg soil) and observed a significant reduction in dehydrogenase activity with increasing nickel doses. The inhibition of dehydrogenase by nickel may be due to the metal's interference with microbial metabolism and its binding to enzyme active sites, preventing their normal function.

Kucharski et al. (2009) confirmed that nickel contamination negatively impacts the activity of dehydrogenases as well as other soil enzymes such as urease and phosphatases. Adding cellulose to contaminated soil partially mitigated these effects, highlighting the importance of management practices that reduce nickel toxicity. The authors noted that enzyme sensitivity to this trace element follows this order: urease > dehydrogenase > alkaline phosphatase > acid phosphatase > catalase > arylsulfatase > β-glucosidase. Assessing dehydrogenase activity appears to be a more objective indicator of nickel contamination than urease activity, as dehydrogenase response is less soil-type dependent. Burns (1982) also supported the suitability of measuring dehydrogenase activity to determine soil biological conditions.

Nickel in soil can also induce oxidative stress, leading to the production of reactive oxygen species (ROS) that damage microbial cells and inhibit enzymatic activity (Xia et al., 2018).

In soils naturally low in nickel, moderate addition can stimulate urease activity because nickel is an essential cofactor for this enzyme. However, this positive effect is limited to deficient soil and low does (Dalton et al., 1985; CAI ET AL., 2005).

Kalembasa et al. (2014) also observed that nickel doses above 75 mg/kg soil significantly inhibited dehydrogenase activity. Their experiment included three factors: 1. doses of nickel added to the soil (0, 75, 150, and 225 mg/kg soil), 2. liming (0 and 1 Ca source according to 1 Hh of hydrolytic acidity), 3. organic materials (rye straw and lignite/brown coal).

Nickel bioavailability and speciation in the soil are key factors influencing the intensity of its effects on enzymatic activity. The most bioavailable fraction is the one soluble in acetic acid or extracted by DTPA, which shows a strong correlation with the inhibition of soil enzymes. Mitigation strategies, such as the application of organic compounds like humic acid extracted from manure, have shown effectiveness in reducing this bioavailable fraction of Ni, helping to minimize the toxic effects of this trace element on enzymatic activity (Liu et al., 2018; Cai et al., 2005).

The presence of other contaminants, such as flotation reagents like xanthates, used in cellophane production, mineral flotation, and organic syntheses can also increase the bioavailability and toxicity of nickel in the soil environment, amplifying the inhibition of enzymatic activity (Li et al., 2018; Li et al., 2020).

To mitigate the toxic effects of trace elements in soil, several strategies can be implemented. The application of organic compounds, such as biochar derived from açaí seeds, can enhance the soil's nutrient retention capacity and reduce the bioavailability of these contaminants (Mendonça et al., 2024). Liming can neutralize soil acidity, decreasing nickel solubility and its toxicity to soil microorganisms (Vischetti et al., 2022; Kalembasa et al., 2014). Studies showed that the addition of organic materials such as rye straw and brown coal reduced nickel's negative effects, suggesting these practices may be effective in maintaining enzymatic activity in contaminated soils (Kalembasa et al., 2014).

The adverse effect of nickel on soil enzyme activity can also be alleviated by enriching the soil with cellulose, combined with fertilization using ammonium sulfate (Kucharski et al., 2009).

2.2 MICROBIAL BIOMASS AND BASAL RESPIRATION

Soil microbial biomass and basal respiration are fundamental indicators of soil biological activity. There is a positive relationship between these two parameters, as soils with higher microbial biomass tend to exhibit higher basal respiration rates, reflecting greater microbial metabolic activity. However, this relationship can be modulated by various factors, including environmental conditions, soil quality, and the physiological state of microorganisms.

Soils with higher microbial biomass generally show higher rates of basal respiration because there are more active microorganisms involved in the decomposition of organic matter and the release of carbon dioxide (Cheng et al., 2013; Dash & Kujur, 2024; Hofman et al., 2004; Yang et al., 2023). Basal respiration, in turn, reflects the maintenance metabolic activity of these microorganisms and is widely used as an indicator of the soil's decomposition potential (Cheng et al., 2013; Dash & Kujur, 2024; Hofman et al., 2004).

The quality and quantity of organic matter present in the soil are determining factors in this dynamic. Soils rich in organic carbon and with adequate moisture levels simultaneously promote increases in microbial biomass and basal respiration (Yang et al., 2022; Dash & Kujur, 2024; Hofman et al., 2004; Yang et al., 2023). Moreover, the physiological state of microorganisms is essential for interpreting this relationship, since basal respiration is more strongly correlated with active microbial biomass than with total biomass, given that dormant microorganisms contribute insignificantly to respiration (Hofman et al., 2004).

Environmental factors such as temperature, moisture, pH, and the presence of heavy metals exert strong influence over microbial biomass and respiration and can substantially alter the relationship between them (Insam, 1990; Richter et al., 2018; Salazar-Villegas et al., 2016; Yang et al., 2023; Liao & Xie, 2007).

Organic matter and moisture tend to increase both microbial biomass and basal respiration (Yang et al., 2022; Dash & Kujur, 2024; Hofman et al., 2004; Yang et al., 2023). Temperature can positively affect both by promoting greater metabolic activity (Insam, 1990; Salazar-Villegas et al., 2016; Yang et al., 2023). Conversely, the presence of heavy metals reduces these parameters, indicating potential toxicity (Liao & Xie, 2007). High levels of active microbial activity also contribute to the simultaneous increase in biomass and basal respiration (Hofman et al., 2004; Yang et al., 2023).

3 METABOLIC QUOCIENT (qCO_2)

The soil metabolic quotient (qCO_2) is a key indicator of how efficiently soil microbiota utilize carbon. It is calculated as the ratio between basal respiration (CO_2 emission) and microbial biomass. Low qCO_2 values reflect greater microbial efficiency in converting carbon into biomass rather than losing it as CO_2. Conversely, high values suggest lower efficiency or the presence of environmental stressors that increase microbial maintenance energy demands (Cheng et al., 2013; Insam, 1990; Richter et al., 2018; Liao & Xie, 2007).

Degraded or stressed soils often exhibit an imbalance in this relationship, with disproportionately high respiration relative to microbial biomass, indicating dysfunction in the soil system (Dash & Kujur, 2024; Liao & Xie, 2007). In contrast, uncontaminated soils tend to show lower qCO_2 values, typical of balanced ecosystems with healthy and efficient microbial activity. This is commonly found in areas with native vegetation or under sustainable agricultural management, where organic matter is abundant and environmental stress is minimal (Pimentel et al., 2008).

Nickel (Ni) contamination can significantly disrupt microbial biomass and respiration, depending on concentration, exposure time, and soil conditions. High levels of Ni generally reduce both microbial biomass and basal respiration, indicating toxicity and impaired microbial functioning. This results in increased qCO_2, as microorganisms expend more carbon to sustain basic survival, reflecting reduced metabolic efficiency (Malhan et al., 2020; Oorts et al., 2007; Yin-Gan, 2004; Li et al., 2015; Moreno et al., 2003).

Studies indicate that Ni concentrations above 100 mg/kg can reduce microbial biomass by over 75%. However, at lower doses, Ni may initially stimulate microbial activity—a hormetic response (Xia et al., 2018; Oorts et al., 2007; Cai et al., 2007). Nickel also alters microbial community composition, impacting microbial groups with varying sensitivities to the metal (Yin-Gan, 2004; Li et al., 2015).

Despite its toxicity, some nickel-tolerant microorganisms can adapt or proliferate in highly contaminated soils, increasing microbial biomass and functional diversity (Helaoui et al., 2020; Kucharski et al., 2009). Nonetheless, basal respiration typically decreases with rising Ni levels due to microbial stress and reduced activity (Morawska-Płoskonka, 2013; Malhan et al., 2020; Oorts et al., 2007).

These effects may diminish over time through soil processes like metal immobilization, which reduces Ni bioavailability. Environmental factors such as organic matter, hyperaccumulator plants, and earthworm activity can also mitigate the harmful impacts of nickel on microbial biomass and respiration (Helaoui et al., 2020; Xia et al., 2018; Yin-Gan, 2004; Moreno et al., 2003).

In conclusion, high nickel concentrations compromise microbial biomass and respiration, directly harming soil health and biological activity. Given their sensitivity to heavy metals, these microbial parameters serve as effective indicators of environmental stress. Soils with high biological activity are typically associated with more productive and sustainable ecosystems, emphasizing the importance of monitoring these indicators for assessing soil quality (Vieira et al., 2016; Barbosa et al., 2023; Kurmanbayev et al., 2023; Adetunji et al., 2017).

Therefore, high levels of nickel compromise microbial biomass and respiration, directly harming soil health and biological activity. The sensitivity of these parameters to Ni makes them valuable indicators of environmental stress caused by heavy metal contamination. Soils with high biological activity are generally associated with more productive and sustainable environments, reinforcing the importance of monitoring these indicators to assess soil quality (Vieira et al., 2016; Barbosa et al., 2023; Kurmanbayev et al., 2023; Adetunji et al., 2017).

4 FINAL CONSIDERATIONS

The presence of nickel (Ni) in the soil significantly affects the biological and functional properties of the edaphic environment, particularly microbial biomass, enzymatic activity, and basal respiration. Although nickel is an essential micronutrient at low concentrations, its accumulation in the soil, mainly from anthropogenic sources, can lead to toxic effects, inhibiting microbial metabolic activity, compromising essential biogeochemical processes, and reducing soil biological quality.

The sensitivity of enzymes such as dehydrogenase, urease, and phosphatases, along with changes in microbial community composition, demonstrates that these parameters can serve as reliable bioindicators for diagnosing soils contaminated by potentially toxic trace elements.

The importance of mitigation strategies is evident, such as the application of organic matter, liming, and the use of hyperaccumulator plants, which can reduce nickel bioavailability and consequently alleviate its adverse effects. The relationship between microbial biomass and basal respiration (qCO_2) has been shown to depend on the physiological state of microorganisms and environmental factors and is strongly impacted by high nickel concentrations.

Therefore, deepening our understanding of the nickel–soil–microbiota interaction is essential for developing sustainable management practices aimed at preserving soil health, ensuring environmental safety, and maintaining agricultural productivity.

REFERENCES

Adetunji, A., Lewu, F., Mulidzi, R., & Ncube, B. (2017). The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: A review. Journal of Soil Science and Plant Nutrition, 17(3), 794–807. https://doi.org/10.4067/S0718-95162017000300018

Ahmad, K., Khan, Z. I., Ashraf, M., Vallem, E. E., Shah, Z. A., & McDowell, L. R. (2009). Determination of forage concentrations of lead, nickel and chromium in relation to the requirements of grazing ruminants in the Salt Range, Pakistan. Pakistan Journal of Botany, 41(1), 61–65.

Alibakhshi, M., & Khoshgoftarmanesh, A. H. (2015). Effects of nickel nutrition in the mineral form and complexed with histidine in the nitrogen metabolism of onion bulb. Plant Growth Regulation, 75(3), 733–740. https://doi.org/10.1007/s10725-014-9976-0

Andrade, W. P. N. (2023). Níquel e selênio no controle da ferrugem asiática (Phakopsora pachyrhizi Syd. & P. Syd.) e seus efeitos bioquímicos na cultura da soja [Doctoral dissertation, Universidade Federal da Grande Dourados]. Repositório UFGD. http://repositorio.ufgd.edu.br/jspui/handle/prefix/5658

Bai, C., Reilly, C., & Wood, B. W. (2006). Ni deficiency disrupts metabolism of ureides, amino acids, and organic acids of young pecan foliage. Plant Physiology, 140(2), 433–443. https://doi.org/10.1104/pp.105.072983

Barbosa, J., Poggere, G., Corrêa, R., Hungria, M., & Mendes, I. (2023). Soil enzymatic activity in Brazilian biomes under native vegetation and contrasting cropping and management. Applied Soil Ecology, 185, 105014. https://doi.org/10.1016/j.apsoil.2023.105014

Boros-Lajszner, E., Wyszkowska, J., & Kucharski, J. (2017). Use of zeolite to neutralise nickel in a soil environment. Environmental Monitoring and Assessment, 190(1), 23. https://doi.org/10.1007/s10661-017-6427-z

Burns, R. G. (1982). Enzyme activity in soil: Location and a possible role in microbial ecology. Soil Biology and Biochemistry, 14(5), 423–427. https://doi.org/10.1016/0038-0717(82)90099-2

Cai, X., Qiu, R., Chen, G., Zeng, X., & Fang, X. (2007). Response of microbial communities to phytoremediation of nickel contaminated soils. Frontiers of Agriculture in China, 1(3), 289–295. https://doi.org/10.1007/s11703-007-0049-0

Cai, X. D., Qiu, R. L., Tang, Y. T., Fang, X. H., & Chen, G. Z. (2005). Fractions of additive nickel and relationship with enzymatic activities in soil. Acta Scientiarum Naturalium Universitatis Sunyatseni, 44(5), 93–97.

Caldwell, B. (2005). Enzyme activities as a component of soil biodiversity: A review. Pedobiologia, 49(6), 637–644. https://doi.org/10.1016/j.pedobi.2005.06.003

Cheng, F., Peng, X., Zhao, P., Yuan, J., Zhong, C., & Cheng, Y. (2013). Soil microbial biomass, basal respiration and enzyme activity of main forest types in the Qinling Mountains. PLoS ONE, 8(6), e67353. https://doi.org/10.1371/journal.pone.0067353

Dalton, D., Evans, H., & Hanus, F. (1985). Stimulation by nickel of soil microbial urease activity and urease and hydrogenase activities in soybeans grown in a low-nickel soil. Plant and Soil, 88(2), 245–258. https://doi.org/10.1007/BF02182451

Dash, S., & Kujur, M. (2024). Contribution of organic carbon, moisture content, microbial biomass-carbon, and basal soil respiration affecting microbial population in chronosequence manganese mine spoil. Nature Environment and Pollution Technology, 23(4), 1753–1762. https://doi.org/10.46488/nept.2024.v23i04.035

Daunoras, J., Kačergius, A., & Gudiukaitė, R. (2024). Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. Biology, 13(2), 85. https://doi.org/10.3390/biology13020085

Frankenberger, W., & Dick, W. (1983). Relationships between enzyme activities and microbial growth and activity indices in soil. Soil Science Society of America Journal, 47(5), 945–951. https://doi.org/10.2136/sssaj1983.03615995004700050021x

Helaoui, S., Boughattas, I., Hattab, S., Mkhinini, M., & Banni, M. (2020). Assessment of changes on rhizospheric soil microbial biomass, enzymes activities and bacterial functional diversity under nickel stress in presence of alfalfa plants. Soil and Sediment Contamination: An International Journal, 29(7), 823–843. https://doi.org/10.1080/15320383.2020.1771276

Hofman, J., Švihálek, J., & Holoubek, I. (2004). Monitoring microbial biomass and respiration in different soils from the Czech Republic – A summary of results. Environment International, 30(1), 19–30. https://doi.org/10.1016/S0160-4120(03)00142-9

Insam, H. (1990). Are the soil microbial biomass and basal respiration governed by the climatic regime? Soil Biology & Biochemistry, 22(4), 525–532. https://doi.org/10.1016/0038-0717(90)90189-7

Kabata-Pendias, A., & Pendias, H. (2001). Trace elements in soils and plants (3rd ed.). CRC Press.

Kalembasa, D., Kuziemska, B., & Kalembasa, S. (2014). Influence of liming and waste organic materials on the activity of urease and dehydrogenase in soil contaminated with nickel. Inżynieria Ekologiczna, 39, 7–17. https://doi.org/10.12912/2081139X.01

Kucharski, J., Boros, E., & Wyszkowska, J. (2009). Biochemical activity of nickel-contaminated soil. Polish Journal of Environmental Studies, 18(6), 1039–1044.

Kurmanbayev, A., Mussayeva, K., & Yermek, S. (2023). Soil biological activity and its indicators in soil quality monitoring: Mini-review. Pochvovedenie i Agrokhimiya, 3(74), 99–108. https://doi.org/10.51886/1999-740x_2023_3_99

Kutman, B. Y., Kutman, U. B., & Cakmak, I. (2014). Effects of seed nickel reserves or externally supplied nickel on the growth, nitrogen metabolites and nitrogen use efficiency of urea- or nitrate-fed soybean. Plant and Soil, 376(1–2), 261–276. https://doi.org/10.1007/s11104-013-1980-2

Levakov, I., Vestergård, M., & Blagodatskaya, E. (2021). Continuous in-situ measurement of free extracellular enzyme activity as direct indicator for soil biological activity. Soil Biology and Biochemistry, 162, 108448. https://doi.org/10.1016/j.soilbio.2021.108448

Li, H., Chen, J., Yang, L., Li, Y., & Chen, G. (2020). Effects of typical flotation reagent on microbial toxicity and nickel bioavailability in soil. Chemosphere, 240, 124913. https://doi.org/10.1016/j.chemosphere.2019.124913

Li, H., Yang, L., Chen, J., Li, Y., & Chen, G. (2018). Microcalorimetry and enzyme activity to determine the effect of nickel and sodium butyl xanthate on soil microbial community. Ecotoxicology and Environmental Safety, 163, 577–584. https://doi.org/10.1016/j.ecoenv.2018.07.108

Li, J., Zhou, X., Yan, J., Li, H., & He, J. (2015). Long-term nickel exposure altered the bacterial community composition but not diversity in two contrasting agricultural soils. Environmental Science and Pollution Research, 22(14), 10496–10505. https://doi.org/10.1007/s11356-015-4232-1

Liao, M., & Xie, X. (2007). Effect of heavy metals on substrate utilization pattern, biomass, and activity of microbial communities in a reclaimed mining wasteland of red soil area.

Ecotoxicology and Environmental Safety, 66(2), 217–223. https://doi.org/10.1016/j.ecoenv.2005.12.013

Liu, B., Huang, Q., Su, Y., Sun, L., & Wu, J. (2018). Speciation of nickel and enzyme activities in fluvo-aquic soil under organic amendments treatment. Soil Research, 56(5), 456–467. https://doi.org/10.1071/SR17330

Malhan, M., Hojati, S., & Enayatizamir, N. (2020). Determination of ED50 in a calcareous soil contaminated with different concentrations of Ni. Journal of Environmental Science and Technology, 22(7), 237–248. https://doi.org/10.22034/JEST.2020.17578

Memoli, V., Esposito, F., Panico, S. C., De Marco, A., & Maisto, G. (2018). Soil element fractions affect phyt Ascent. The Science of the Total Environment, 636*, 1099–1108. https://doi.org/10.1016/j.scitotenv.2018.04.327

Mendonça, M. S., Xavier, R. P., Lima, A. T., & Faria, R. M. (2024). Acai seed biochar improves soil quality and black pepper seedling development in the Amazon Region. Journal of Environmental Management, 367, 121752. https://doi.org/10.1016/j.jenvman.2024.121752

Morawska-Płoskonka, J. (2013). Effects of soil moisture and nickel contamination on microbial respiration rates in heavy metal-polluted soils. Polish Journal of Environmental Studies, 22(3), 779–785.

Moreno, J., Merino, M., Ramírez, M., & Ondoño, E. (2003). The ecological dose of nickel in a semiarid soil amended with sewage sludge related to the unamended soil. Water, Air, and Soil Pollution, 143(1–4), 289–300. https://doi.org/10.1023/A:1022853812926

Nannipieri, P., Trasar-Cepeda, C., & Dick, R. (2017). Soil enzyme activity: A brief history and biochemistry as a basis for appropriate interpretations and meta-analysis. Biology and Fertility of Soils, 54(1), 11–19. https://doi.org/10.1007/s00374-017-1245-6

Nowak, J., Gliński, J., & Stępniewska, Z. (2000). Soil enzymatic activity as an indicator of soil pollution by heavy metals. Polish Journal of Environmental Studies, 9(6), 493–499.

Oorts, K., Ghesquiere, U., & Smolders, E. (2007). Leaching and aging decrease nickel toxicity to soil microbial processes in soils freshly spiked with nickel chloride. Environmental Toxicology and Chemistry, 26(6), 1130–1138. https://doi.org/10.1897/06-533R.1

Pimentel, M. S., Faria, R. M., Almeida, C. M. V. B., & Xavier, R. P. (2008). Atributos químicos e microbianos do solo sob diferentes manejos no município de Seropédica, RJ. Current Agricultural Science and Technology, 14(2), 1–10. https://periodicos.ufpel.edu.br/index.php/CAST/issue/view/134

Piotrowska-Długosz, A., Charzyński, P., & Siwak, D. (2022). Enzymatic activity and functional diversity of soil microorganisms along the soil profile – A matter of soil depth and soil-forming processes. Geoderma, 416, 115779. https://doi.org/10.1016/j.geoderma.2022.115779

Ren, C., Liu, W., Zhao, F., Zhang, L., & Wang, J. (2021). Contrasting patterns of microbial community and enzyme activity between rhizosphere and bulk soil along an elevation gradient. Catena, 196, 104921. https://doi.org/10.1016/j.catena.2020.104921

Ren, H., Li, H., Zhang, Q., Wang, L., & Zhang, J. (2023). Understanding the physiological mechanisms of canopy light interception and nitrogen distribution characteristics of different maize varieties at varying nitrogen application levels. Agronomy, 13(4), 1146. https://doi.org/10.3390/agronomy13041146

Richter, A., O'Callaghan, M., & Reuman, D. C. (2018). Linking diagnostic features to soil microbial biomass and respiration in agricultural grassland soil: A large-scale study in Ireland. European Journal of Soil Science, 69(3), 414–428. https://doi.org/10.1111/ejss.12551

Salazar-Villegas, A., Blagodatskaya, E., & Dukes, J. S. (2016). Changes in the size of the active microbial pool explain short-term soil respiratory responses to temperature and moisture. Frontiers in Microbiology, 7, 524. https://doi.org/10.3389/fmicb.2016.00524

Tan, X., Yang, Y., Liu, B., & Zhang, L. (2021). Soil chemical properties rather than the abundance of active and potentially active microorganisms control soil enzyme kinetics. The Science of the Total Environment, 770, 144500. https://doi.org/10.1016/j.scitotenv.2020.144500

Tecon, R., & Or, D. (2017). Biophysical processes supporting the diversity of microbial life in soil. FEMS Microbiology Reviews, 41(5), 599–623. https://doi.org/10.1093/femsre/fux039

Trus, O., Prokopenko, E., & Polishchuk, T. (2021). Biological activity of soil, its importance for soil fertility and plant nutrition. Transactions of Kremenchuk Mykhailo Ostrohradskyi National University, 5(130), 36–41. https://doi.org/10.30929/1995-0519.2021.5.36-41

Vieira, A. C., Xavier, R. P., Faria, R. M., & Silva, J. R. (2016). Fogo e seus efeitos na qualidade do solo de pastagem. Revista Brasileira de Geografia Física, 9(6), 11–23. https://periodicos.ufpe.br/revistas/index.php/rbgfe/article/view/233918

Vischetti, C., Coppola, L., & Marini, M. (2022). Nickel in the environment: Bioremediation techniques for soils with low or moderate contamination in European Union. Environments, 9(10), 133. https://doi.org/10.3390/environments9100133

Wang, X., Zhang, W., Liu, Y., & Zhao, Z. (2023). Soil extracellular enzyme stoichiometry reflects microbial metabolic limitations in different desert types of northwestern China. The Science of the Total Environment, 856(Pt 2), 162504. https://doi.org/10.1016/j.scitotenv.2023.162504

Wyszkowska, J., Kucharski, J., & Boros, E. (2005). Effect of nickel contamination on soil enzymatic activities. Plant, Soil and Environment, 51(12), 523–531. https://doi.org/10.17221/3627-PSE

Xia, X., Duan, B., Dai, C., & Wu, Y. (2018). Toxic responses of microorganisms to nickel exposure in farmland soil in the presence of earthworm (Eisenia fetida). Chemosphere, 192, 43–50. https://doi.org/10.1016/j.chemosphere.2017.10.146

Xiao, R., Duan, B., Dai, C., & Wu, Y. (2024). Soil enzyme activities and microbial nutrient limitation of various temperate forest types in Northeastern China. Forests, 15(10), 1815. https://doi.org/10.3390/f15101815

Xing, W., Zhang, L., Yang, Y., & Liu, B. (2024). Soil enzyme profile analysis for indicating decomposer micro-food web. iMeta, 3(1), e161. https://doi.org/10.1002/imt2.161

Yang, L., Zhang, L., Liu, B., & Wu, J. (2023). Soil microbial respiration adapts to higher and longer warming experiments at the global scale. Environmental Research Letters, 18(4), 044027. https://doi.org/10.1088/1748-9326/acbecb

Yang, Y., Zhang, L., Liu, B., & Wu, J. (2022). Interactions between soil organic matter chemical structure and microbial communities determine the spatial variation of soil basal respiration in boreal forests. Applied Soil Ecology, 178, 104743. https://doi.org/10.1016/j.apsoil.2022.104743

Yin-Gan, L. (2004). Effect of microbial ecology in restoring ecology of yellow soils polluted by heavy metal nickel. Journal of Soil and Water Conservation, 18(5), 19–22.

Yudina, A., Fomin, S., & Kuzyakov, Y. (2023). Localization of C cycle enzymes in arable and forest Phaeozems within levels of soil microstructure. Microorganisms, 11(5), 1343. https://doi.org/10.3390/microorganisms11051343