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Zbornik radova

“Gospodarenje tlom i interdisciplinarni pristupi globalnim izazovima”



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Proceedings

“Soil Management and Interdisciplinary Approaches to Global Challenges”

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POZDRAVNA RIJEČ



Poštovane kolegice i kolege, uvaženi gosti, dragi sudionici i prijatelji Hrvatskog tloznanstvenog društva, s osobitim zadovoljstvom želimo vam dobrodošlicu na 15. Kongres Hrvatskog tloznanstvenog društva, koji se od 14. do 18. rujna 2026. godine održava u Vodicama pod naslovom „Gospodarenje tлом i interdisciplinarni pristupi globalnim izazovima“. Tlo je jedan od temeljnih prirodnih resursa i nezamjenjiva sastavnica kopnenih ekosustava. Ono je osnova proizvodnje hrane i biomase, ima ključnu ulogu u kruženju hraniva i vode, očuvanju bioraznolikosti i regulaciji brojnih procesa u okolišu. Unatoč njegovoj iznimnoj važnosti, tlo je izloženo sve snažnijim pritiscima i degradacijskim procesima, zbog čega njegovo očuvanje i održivo gospodarenje postaju jedni od važnijih izazova suvremenog društva.

Klimatske promjene, erozija, smanjenje sadržaja organske tvari, zbijanje tla, onečišćenje, gubitak bioraznolikosti, prenamjena zemljišta te sve veći zahtjevi za proizvodnjom hrane dodatno naglašavaju potrebu za odgovornim i znanstveno utemeljenim upravljanjem tлом. Istodobno, od tla se očekuje da odgovori na brojne i često međusobno povezane zahtjeve – od osiguravanja stabilne poljoprivredne proizvodnje do očuvanja ekosustava i prilagodbe klimatskim promjenama. Upravo zato tema ovogodišnjega Kongresa posebno naglašava interdisciplinarni pristup. Suvremeni izazovi povezani s tлом nadilaze granice pojedinih znanstvenih disciplina te zahtijevaju povezivanje različitih znanja, metoda i iskustava. Suradnja stručnjaka iz područja pedologije, agronomije, šumarstva, ekologije, biologije, hidrologije, geografije, zaštite okoliša, prostornog planiranja i drugih srodnih područja nužna je kako bi se složeni procesi koji se odvijaju u tlu bolje razumjeli, a mjere njegova očuvanja i gospodarenja bile što učinkovitije. Kongres Hrvatskog tloznanstvenog društva tradicionalno predstavlja mjesto susreta znanstvenika, stručnjaka, nastavnika, mladih istraživača i drugih dionika čiji je rad povezan s tлом. Plenarna i usmena izlaganja, posterska priopćenja, stručne rasprave, okrugli stol te terenski dio programa pružaju priliku za predstavljanje novih rezultata istraživanja, razmjenu iskustava i sagledavanje aktualnih pitanja iz različitih perspektiva. Posebno je važna mogućnost povezivanja znanstvenih spoznaja s praktičnim iskustvima i potrebama društva. Rezultati istraživanja tla svoju punu vrijednost ostvaruju kada postanu osnova za donošenje kvalitetnih odluka o načinu korištenja prostora, poljoprivrednoj proizvodnji, zaštiti okoliša i očuvanju prirodnih resursa. Stoga ovakvi susreti imaju važnu ulogu u stvaranju dijaloga između znanosti, struke i prakse. Jednako je vrijedna i njihova uloga u povezivanju različitih generacija istraživača. Razmjena iskustava između etabliranih stručnjaka i mladih znanstvenika pridonosi razvoju novih ideja, istraživačkih pristupa i suradnji te osigurava kontinuitet razvoja znanosti o tlu. Vjerujemo da će 15. Kongres Hrvatskog tloznanstvenog društva biti mjesto kvalitetnih znanstvenih i stručnih rasprava, novih spoznaja i ideja, ali i prilika za stvaranje novih i jačanje postojećih suradnji. Nadamo se da će zajednički rad i razmjena iskustava pridonijeti boljem razumijevanju tla te pronalaženju učinkovitih i održivih odgovora na izazove koji su pred nama. Zahvaljujemo svim sudionicima, autorima, predavačima, članovima kongresnih tijela, suradnicima i institucijama koji su svojim radom i sudjelovanjem pridonijeli organizaciji i kvaliteti Kongresa.

Želimo vam uspješan i sadržajan Kongres, poticajne rasprave, nova znanja i suradnje te ugodan boravak u Vodicama.

Dobro došli na 15. Kongres Hrvatskog tloznanstvenog društva!

S poštovanjem,
Predsjednik Hrvatskog tloznanstvenog društva

WELCOME ADDRESS

Dear colleagues, distinguished guests, dear participants and friends of the Croatian Society of Soil Science, It is our great pleasure to welcome you to the 15th Congress of the Croatian Society of Soil Science, held in Vodice from 14 to 18 September 2026 under the theme “Soil Management and Interdisciplinary Approaches to Global Challenges”. Soil is one of our most fundamental natural resources and an indispensable component of terrestrial ecosystems. It forms the basis of food and biomass production and plays a key role in nutrient and water cycling, biodiversity conservation, and the regulation of numerous environmental processes. Despite its exceptional importance, soil is increasingly exposed to various pressures and degradation processes, making its protection and sustainable management one of the major challenges facing modern society. Climate change, erosion, the decline of soil organic matter, soil compaction, pollution, biodiversity loss, land-use change, and the growing demand for food production further emphasize the need for responsible and science-based soil management. At the same time, soils are expected to meet numerous and often interconnected demands – from ensuring stable agricultural production to preserving ecosystems and supporting adaptation to climate change. For this reason, the theme of this year’s Congress places particular emphasis on an interdisciplinary approach. Contemporary soil-related challenges extend beyond the boundaries of individual scientific disciplines and require the integration of different areas of knowledge, methodologies, and practical experience. Cooperation among experts in soil science, agronomy, forestry, ecology, biology, hydrology, geography, environmental protection, spatial planning, and other related fields is essential for a better understanding of complex soil processes and for developing effective approaches to soil protection and management. The Congress of the Croatian Society of Soil Science traditionally provides a meeting place for scientists, professionals, educators, young researchers, and other stakeholders whose work is related to soil. Plenary and oral presentations, poster contributions, professional discussions, the round table, and the field programme offer opportunities to present new research results, exchange experience, and address current issues from different perspectives. Particularly important is the opportunity to connect scientific knowledge with practical experience and societal needs. Soil research achieves its full value when its findings provide a sound basis for informed decisions concerning land use, agricultural production, environmental protection, and the conservation of natural resources. Meetings such as this Congress therefore play an important role in strengthening dialogue between science, the profession, and practice. Equally valuable is their role in connecting different generations of researchers. The exchange of knowledge and experience between established experts and young scientists contributes to the development of new ideas, research approaches, and collaborations, while also ensuring continuity in the advancement of soil science. We believe that the 15th Congress of the Croatian Society of Soil Science will provide a stimulating environment for high-quality scientific and professional discussions, new knowledge and ideas, as well as opportunities to establish new partnerships and strengthen existing collaborations. We hope that our shared work and exchange of experience will contribute to a better understanding of soils and to the development of effective and sustainable responses to the challenges ahead. We sincerely thank all participants, authors, speakers, members of the Congress committees, collaborators, and institutions whose work and involvement have contributed to the organization and quality of the Congress.

We wish you a successful and inspiring Congress, fruitful discussions, new knowledge and collaborations, and an enjoyable stay in Vodice.

Welcome to the 15th Congress of the Croatian Society of Soil Science!

Sincerely,
President of the Croatian Society of Soil Science



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Microbial biomass and cellulose decomposition as indicators of early brownfield soil recovery

Alexandra Balódi, Zuzana Feketeová, Malvína Reiffers Čierniková, Sanja Nosalj

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Abstract

The restoration of degraded soils represents an important challenge in regions affected by abandoned or underutilized land. Organic amendments such as compost are frequently used to improve soil properties and stimulate biological processes during ecological restoration. The aim of this study was to evaluate short-term changes in microbial biomass carbon and cellulolytic activity following compost application in degraded brownfield soil. Soil samples were collected from a brownfield site undergoing ecological revitalization in southwestern Slovakia. Compost was applied during the planting of fruit trees, and soil samples were subsequently collected at three sampling times over a ten-month period. Microbial biomass carbon (MBC) was used as an indicator of microbial abundance, while cellulolytic activity (Ac) represented the rate of cellulose decomposition and overall decomposition potential of the soil microbial community.

The results showed a pronounced increase in microbial biomass shortly after compost application. Mean MBC increased from approximately 98.6 $\mu\text{g C g}^{-1}$ soil before compost application to 181.5 $\mu\text{g C g}^{-1}$ soil after four months, indicating rapid microbial activation in response to the input of organic substrates. Although MBC slightly decreased during the later sampling stage (172.8 $\mu\text{g C g}^{-1}$ soil), values remained substantially higher than the initial baseline, suggesting sustained stimulation of microbial biomass. At the same time, cellulolytic activity showed a progressive increase during the experimental period, indicating enhanced decomposition processes associated with the transformation of organic residues introduced with the compost amendment. These changes suggest that compost addition stimulated both microbial growth and the capacity of the soil microbial community to decompose organic substrates.

Overall, the observed patterns indicate that compost amendment rapidly activates microbial processes in degraded brownfield soils and supports increased decomposition activity during the early stages of soil recovery. The results highlight the potential of compost application as an effective strategy for stimulating biological processes during ecological restoration of degraded soils.

Key words: brownfield soil, cellulolytic activity, compost amendment, microbial biomass carbon, soil restoration



Introduction

Soil degradation represents a significant environmental and socio-economic problem that negatively affects soil productivity, ecosystem functioning, biodiversity, and human well-being. It results from both natural processes and human activities, including erosion, leaching, nutrient depletion, acidification, salinization, contamination and unsustainable land management practices (Blaikie and Brookfield, 1987). Brownfields are a specific type of degraded land, typically consisting of abandoned or underused industrial and commercial sites whose redevelopment is hindered by real or perceived contamination. These areas often require comprehensive and sustainable remediation strategies to restore their environmental, economic, and social functions (He et al., 2024).

Application of organic fertilizers, particularly compost, is one of the most effective and environmentally friendly approaches for improving the properties of degraded soils. Composting is an aerobic microbial process that transforms organic waste into stable organic material under controlled conditions, suitable for agricultural and landscape management, while also contributing to sustainable waste and resource management (Rynk et al., 2022). Compost supplies stable organic carbon, essential nutrients, and diverse microbial communities, while improving key physical properties such as aggregation, porosity, and water retention, as well as chemical characteristics including pH, nutrient availability, and sorption capacity (Glab et al., 2025). By stimulating microbial communities, which rapidly respond to the input of readily degradable organic substrates with increased biomass, respiration, and diversity, compost enhances key soil processes such as nutrient cycling, organic matter decomposition, and soil structure formation (Ros et al., 2003). These effects support overall soil recovery, long-term sustainable land use, and help limit the expansion of urbanized areas at the expense of natural environments.

The aim of this study was to emphasize the importance of soil degradation as an environmental concern and to evaluate the potential of biological reclamation using organic fertilizers. The research specifically examines the impact of compost application on soil microbiological properties, focusing on microbial biomass carbon and cellulolytic activity, by comparing soil conditions before and after the amendment during the reclamation process.

Material and Methods

Soil sampling was carried out in Vydrany, a village in southwestern Slovakia. The study included three contrasting sites – the edge of agricultural land, an area adjacent to a moderately trafficked road, and a small, neglected plot on the village outskirts. The study sites represented heterogeneous brownfield soils differing in texture, pH and organic carbon content. Sampling was performed at three stages, prior to restoration in November (T0), four months after compost application in March (T1) and six months later in September (T2).

During the first sampling (T0), topsoil samples (0–15 cm) were collected using a soil probe. At the same time, fruit trees were planted (S1, S2 – plum; H1-H3 – pear; M1, M2 – mulberry; G1-G3- chestnut), and Hoštický garden compost from Czech Republic was applied to each planting pit at approximately 2 kg per tree. This was the only compost application performed during the study. The plantation included sweet chestnut (*Castanea sativa* Miller, 1768), white mulberry (*Morus alba* Linnaeus, 1753), common pear (*Pyrus communis* Linnaeus, 1753), and domestic plum (*Prunus domestica* Linnaeus, 1753), with species distribution varying across sites.

The second (T1) and third (T2) sampling followed the same procedure at the same locations, with soil collected from the upper 15 cm beneath the planted trees.

Collected soil samples were first cleared of larger rock fragments and plant material, then sieved to the <2 mm fraction for analysis.



Microbial biomass carbon (MBC) was quantified using the chloroform fumigation-extraction technique according to Vance et al. (1987). Freshly collected soil samples were exposed to ethanol-free chloroform vapor for 24 hours to lyse microbial cells. Parallel non-fumigated samples were maintained as controls. Both fumigated and control soils were then extracted with 0.5 M K₂SO₄ at a soil-to-extractant ratio of 1:4. The concentration of extractable organic carbon in the extracts was measured via dichromate oxidation, followed by back-titration with Mohr's salt. Microbial biomass carbon was calculated using the difference between fumigated and non-fumigated extractable carbon, divided by the conversion factor $k_{EC} = 0.45$, which accounts for the fraction of microbial carbon recovered during extraction: $MBC = (C_{fum} - C_{nof})/k_{EC}$. This procedure provides an estimate of the carbon contained within the living microbial population in the soil.

Cellulolytic activity (Ac) of soil microorganisms was estimated using a modified Grund method (Nosalj and Šimonovičová, 2022), which quantifies the rate of cellulose decomposition under controlled laboratory conditions. Soil microorganisms produce cellulolytic enzymes that enable the breakdown of complex organic compounds. Given the recalcitrant nature of cellulose, its degradation serves as a sensitive indicator of the capacity of soil microbial communities to decompose resistant plant tissues. For evaluation, soil samples were evenly distributed in Petri dishes, and the surface was lightly moistened. Six strips of sterile filter paper were placed on each sample, and the samples were incubated for 12 weeks, with moisture levels monitored periodically. Following incubation, the extent of cellulose decomposition was determined using a square-grid template, providing a quantitative measure of microbial cellulolytic activity.

Results and Discussion

Following compost amendment, microbial biomass carbon (MBC) exhibited a clear upward shift compared to the initial soil condition (Fig. 1). The lowest levels were recorded prior to treatment (T0), whereas substantially higher values were observed after compost addition (T1). Between T1 and T2, however, different trends were observed among the sampling sites. While MBC continued to increase in samples S1, H1, and G3, a moderate decline was recorded in the remaining sites. Despite this decrease, MBC values at T2 generally remained considerably higher than those measured before compost application, suggesting a sustained positive effect of the amendment on microbial biomass. Statistical evaluation confirmed significant differences between T0 and both subsequent sampling dates, while no significant change was detected between T1 and T2. On average, MBC increased markedly from 98.6 $\mu\text{g C g}^{-1}$ soil at T0 to 181.5 $\mu\text{g C g}^{-1}$ soil at T1, reflecting a rapid microbial response to the input of organic substrates. Although a slight decrease was observed at T2 (172.8 $\mu\text{g C g}^{-1}$ soil), mean values remained substantially higher than the initial baseline, indicating that the stimulatory effect of compost amendment was sustained over the monitoring period.

The observed pattern suggests a rapid response of the soil microbial community to the incorporation of organic material, followed by a stabilization phase. The initial increase after amendment reflects enhanced microbial utilization of newly introduced organic substrates, which likely stimulated microbial growth and activity (Prommer et al., 2019). In the following period, the system appears to have stabilized, as indicated by the absence of further significant changes between T1 and T2. Similar responses have been reported in soils where the initial stimulation induced by organic amendments is followed by a stabilization phase characterized by reduced microbial growth rates. This effect can be particularly pronounced in soils with low levels of stable organic matter or limited availability of nitrogen and phosphorus (Diacono and Montemurro, 2010).



Sustained higher MBC values at T2 compared to the initial state indicate that compost application induced a longer-term modification of soil biological conditions rather than a short-lived stimulation. This persistence suggests that part of the added organic matter was progressively integrated into soil organic pools, supporting continued microbial presence and activity over time. Such responses are commonly associated with organic amendments that enhance substrate availability and improve habitat conditions for soil microorganisms, thereby shifting the functional status of the soil system (Liu et al., 2022).

In contrast, sites exhibiting a continued increase in MBC, such as S1, H1, and G3, may have supported more stable microbial populations or benefited from a more gradual release of nutrients from the compost, allowing microbial biomass to continue accumulating over time (Ryckeboer et al., 2003).

Overall, the results demonstrate that compost application led to a sustained enhancement of microbial biomass and a progressive stabilization of soil biological properties across the monitored period.

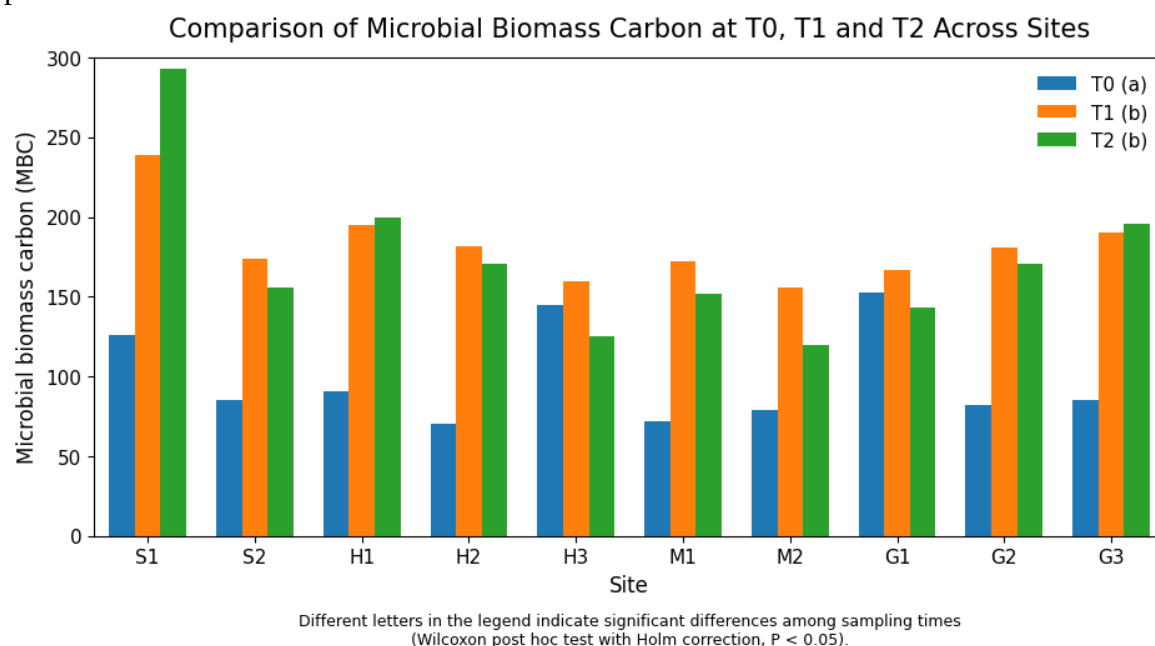


Figure 1. Microbial biomass carbon (MBC) measured at 0–15 cm depth across ten brownfield sites before compost application (T0) and approximately 4 months (T1) and 10 months (T2) after application. The letters refer to the overall comparison among sampling times across all sites and do not indicate statistical differences within individual sites.

Cellulose decomposition, expressed as the cellulolytic activity level (Ac), exhibited a clear temporal response to compost application. Overall, Ac values decreased after treatment compared with the initial state (T0), indicating enhanced cellulose decomposition, as lower Ac values correspond to higher cellulolytic activity. Statistical analysis confirmed a significant effect of sampling time on decomposition intensity. Significant differences were detected between T0 and both T1 and T2, whereas no significant difference was observed between T1 and T2. This pattern suggests that the major functional shift occurred shortly after compost application and was subsequently maintained throughout the experiment.



The most pronounced change was observed during the early phase (T0–T1), suggesting that the newly introduced organic substrates provided an immediate energy source for cellulolytic microorganisms, thereby stimulating microbial decomposition processes. Thereafter, decomposition activity remained relatively stable, indicating that the microbial community had reached a new functional equilibrium (Prommer et al., 2019).

At the first post-application assessment (T1), cellulolytic activity improved in most sampling sites, with 8 out of 10 sites showing lower Ac values than at T0. Only S1 and S2 remained unchanged. This indicates that the microbial response to compost addition was already evident shortly after application, although its intensity varied among locations. A similar pattern persisted at T2, where 8 of the 10 sites still exhibited lower Ac values relative to the initial condition. However, M1 and M2 deviated from this trend, displaying slightly higher Ac values than at T0, which indicates a reduction in cellulolytic activity compared with the baseline. Despite these exceptions, most sites maintained enhanced cellulose decomposition capacity over time.

Considerable spatial variability was evident among sampling sites. The strongest improvements were recorded at H3, H1, and S1, where substantial decreases in Ac values from T0 to T2 reflected enhanced cellulose decomposition capacity. H3 responded rapidly, showing a marked improvement already at T1 that persisted until the end of the experiment. In contrast, H1 and S1 exhibited a more gradual response, with the largest reductions in Ac values occurring at the final sampling stage. Sites G2 and G3 displayed a moderate but stable response, with intermediate Ac values throughout the study period, suggesting a balanced yet less pronounced stimulation of cellulolytic activity. H2 and G1 showed a slower but consistent improvement, with Ac values gradually decreasing over time, indicating delayed activation of cellulolytic microbial processes. The S group exhibited an overall positive response to compost amendment; however, cellulolytic activity remained largely unchanged during the initial phase (T1). Enhanced cellulose decomposition became evident only at the final sampling stage (T2), suggesting a delayed microbial response to the added organic substrates. In contrast, the M group (M1 and M2) showed little overall change in cellulolytic activity during the experiment, indicating a relatively stable but weakly responsive microbial system. This response may be associated with limiting abiotic soil factors that constrain cellulolytic microbial activity even after compost application (Datta, 2024). Overall, compost application resulted in a moderate but consistent enhancement of cellulolytic activity, reflecting increased organic matter inputs to the soil. The added organic substrates likely stimulated microbial decomposition processes and promoted cellulose degradation. In sites exhibiting strong improvements, particularly H3, H1, and S1, the response may be linked to the activation of previously dormant or low-activity cellulolytic microorganisms following substrate enrichment. Conversely, the weak response observed in M1 and M2 suggests limited biological reactivity, potentially caused by unfavourable physico-chemical soil conditions or a low abundance of active cellulolytic microbial populations (Datta, 2024). Enhanced decomposition dynamics may also contribute to the gradual transformation of organic matter and the formation of more stable humus fractions (Lehmann and Kleber, 2015), indicating an overall improvement in soil functional status.

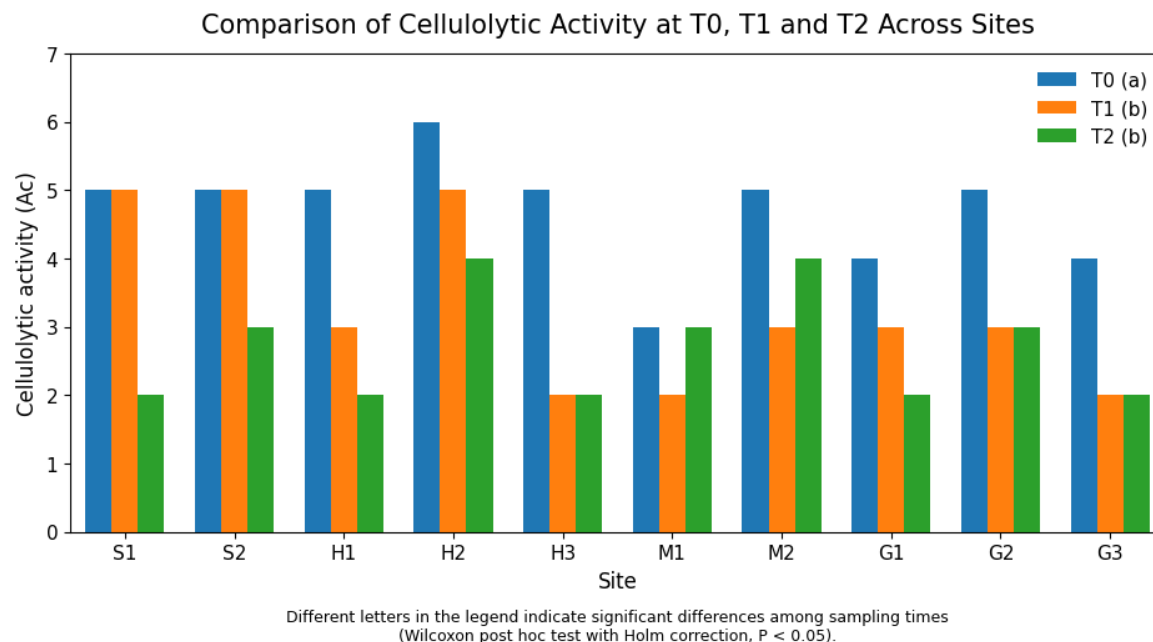


Figure 2. Cellulolytic activity (Ac) measured at 0–15 cm depth across ten brownfield sites before compost application (T0) and approximately 4 months (T1) and 10 months (T2) after application. Lower Ac values indicate higher cellulolytic activity. The letters refer to the overall comparison among sampling times across all sites and do not indicate statistical differences within individual sites.

Foot note: Lower Ac values indicate higher cellulolytic activity

Conclusion

Compost application induced significant changes in soil biological activity, reflected by both increased microbial biomass carbon (MBC) and enhanced cellulolytic activity. The most pronounced response occurred shortly after amendment, when microbial biomass increased markedly and cellulose decomposition intensified, indicating rapid utilization of newly introduced organic substrates by soil microorganisms. Although no further significant changes were detected between the subsequent sampling dates, both parameters remained improved relative to the initial state, demonstrating a sustained positive effect of compost on soil biological functioning.

The observed enhancement of cellulolytic activity suggests increased functional activity of decomposer communities involved in organic matter degradation, while elevated MBC values indicate the development and maintenance of a larger active microbial biomass. Together, these responses highlight the role of compost as an effective source of carbon and energy that stimulates microbial processes and promotes soil biological quality. Despite the overall positive trend, considerable spatial variability was observed among sampling sites, indicating that local soil conditions influenced the magnitude and persistence of microbial responses. Sites exhibiting strong and sustained improvements likely provided more favourable conditions for microbial growth and decomposition processes, whereas weaker responses may have been constrained by abiotic limitations or differences in microbial community composition. Overall, the results demonstrate that compost amendment contributes not only to a short-term stimulation of microbial activity but also to longer-term improvements in soil functional status through enhanced microbial biomass and accelerated organic matter decomposition. These processes may support the gradual transformation of organic matter into more stable soil organic fractions, thereby contributing to improved soil quality and ecosystem functioning. The findings support the use of compost amendment as a practical tool for the initial restoration of degraded brownfield soils, although long-term monitoring is needed to evaluate the persistence of these improvements.



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Intercropping in conservation agriculture: A path towards more resilient and sustainable agroecosystems

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Abstract

Intercropping represents an important agroecological practice that can contribute to the sustainability and resilience of agricultural production. The cultivation of two or more plant species on the same production area enables more efficient use of light, water and nutrients due to differences in plant morphology, growth dynamics and resource requirements. Within conservation agriculture, intercropping contributes to increased crop diversity, improved soil cover and more efficient use of natural resources. Greater diversity of plant residues and root systems can improve soil biological activity, nutrient cycling, soil structure and water use efficiency, while increased biomass inputs may contribute to the preservation of soil organic carbon. Intercropping can also improve the resilience of production systems to adverse environmental conditions and contribute to climate change adaptation. However, its effectiveness depends on plant species selection, agroecological conditions and management practices. Further long-term research is needed to evaluate changes in soil health and to develop intercropping systems adapted to different production conditions.

Key words: climate resilience, crop diversification, soil health, sustainable agriculture

Introduction

Agricultural production today faces the challenge of ensuring stable food production while preserving natural resources and adapting to increasingly pronounced climate change. Increasing average air temperatures, changes in the distribution and intensity of precipitation, and the increasing frequency of extreme weather events negatively affect crop productivity, water availability, and soil quality, particularly in systems that rely on intensive tillage and simplified crop rotations (Altieri et al., 2015; IPCC, 2023). At the same time, the long-term use of intensive production systems has contributed to the reduction of organic matter content, soil structure degradation, increased erosion, and biodiversity loss, which threatens the long-term sustainability of agricultural production (Lal, 2015; FAO, 2022).

Increasing attention is being paid to sustainable crop production systems that enable the conservation of natural resources while reducing dependence on external inputs. In this context, conservation agriculture represents one of the most significant sustainable approaches in plant production, and is based on minimal soil disturbance, permanent soil cover and proper crop rotation (FAO, 2017; Jug et al., 2018). The adoption of conservation agriculture principles contributes to the preservation of soil fertility, more efficient use of water and nutrients, and increasing the resistance of agroecosystems to abiotic and biotic stresses (Pittelkow et al., 2015). A greater variety of crops in crop rotations is one of the fundamental principles of conservation agriculture, with intercropping occupying an increasingly important place both in scientific research and in agricultural practice. Intercropping, unlike sole cropping, in which plants use the same resources at approximately the same time and in a similar way, allows for more efficient use of light, water, nutrients and vegetation space (Lithourgidis et al., 2011; Brooker et al., 2015;



Martin-Guay et al., 2018). Intercropping can increase the efficiency of natural resource use and contribute to greater stability and sustainability of crop production in changing agro-ecological conditions (Martin-Guay et al., 2018; Glaze-Corcoran et al., 2020). In addition to its effects on productivity, intercropping also plays an important role in preserving the functionality of agro-ecosystems. Increased crop rotation diversity has a positive effect on the dynamics of organic matter, microbial activity and nutrient cycling, which contributes to the improvement of the chemical, physical and biological properties of the soil (Bünemann et al., 2018; Tamburini et al., 2020). At the same time, intercropping systems create more favorable conditions for the development of beneficial organisms, while increasing the resistance of production systems to abiotic and biotic stresses and contributing to the long-term sustainability of agricultural production (Tamburini et al., 2020; Glaze-Corcoran et al., 2020). Therefore, intercropping is now considered one of the important agroecological strategies for increasing the resilience of production systems in the present climate change conditions (Beillouin et al., 2019; Burgess et al., 2022). The aim of this review paper is to present current knowledge on the role of intercropping in conservation agriculture, with a particular emphasis on its contribution to agroecosystem functionality, soil health, more efficient use of natural resources, and increasing the resilience of agricultural production in the face of climate change.

Intercropping as a component of conservation agriculture

Conservation agriculture is based on principles that aim to support sustainable agricultural production while preserving natural soil processes and ecosystem functions (Pittelkow et al., 2015; FAO, 2017). Its effectiveness is based on the combined benefits of minimal soil disturbance, permanent soil cover, and increased crop diversity. Intercropping involves the simultaneous cultivation of two or more plant species on the same production area during entire or part of the growing season (Lithourgidis et al., 2011). Such production systems are based on the functional complementarity of plant species, whose differences in morphological, physiological and phenological properties allow more efficient use of light, water, nutrients and vegetation space (Brooker et al., 2015; Li et al., 2014). Differences in root system morphology, growth dynamics and resource requirements reduce competition between plants and increase the overall efficiency of the production system (Hauggaard-Nielsen and Jensen, 2005; Brooker et al., 2015). The success of intercropping largely depends on the proper selection of plant species (Brooker et al., 2015). Combinations of legumes and non-legumes are particularly important, in which biological fixation of atmospheric nitrogen contributes to a better supply of this nutrient, while different dynamics of water and nutrient uptake enable their more efficient use during the growing season (Duchene et al., 2017; Hauggaard-Nielsen et al., 2001). Such complementarity often results in higher total biomass production, more efficient use of production area, and more stable yields compared to sole cropping (Willey, 1979; Martin-Guay et al., 2018; Glaze-Corcoran et al., 2020). In addition to increasing productivity, intercropping contributes to the achievement of the fundamental goals of conservation agriculture. Greater diversity of plant species increases the amount and variety of plant residues entering the soil, promotes the development of more diverse microbial communities and more intensive nutrient cycling, and contributes to the preservation of favorable soil structure (Duchene et al., 2017; Tamburini et al., 2020). At the same time, better soil coverage during the growing season reduces the risk of erosion, mitigates temperature fluctuations, and reduces water loss through evaporation (Glaze-Corcoran et al., 2020). When intercropping is combined with other principles of conservation agriculture, its positive effects on soil health and the resilience of the production system are further enhanced (Pittelkow et al., 2015; Beillouin et al., 2019; Tamburini et al., 2020).



Effects of intercropping on soil health and natural resource use

The effects of intercropping cannot be considered only through the achieved yield of individual crops. Its role in enhancing the long-term productivity and resilience of cropping systems is increasingly recognized, particularly through its contribution to soil health, nutrient cycling, biological activity, and water use efficiency (Glaze-Corcoran et al., 2020; Tamburini et al., 2020). Intercropping is therefore considered as an agroecological practice that influences the functioning of the entire agroecosystem. Many of its benefits develop gradually and may become more pronounced with long-term implementation (Beillouin et al., 2019). One of the most important effects of intercropping is the increased quantity and diversity of plant residues and root exudates entering the soil (Duchene et al., 2017).

Different plant species produce organic inputs with different chemical compositions, thereby increasing the diversity of organic substrates available to soil microorganisms. Such conditions encourage the development of more diverse microbial communities that participate in the decomposition of organic matter, the transformation of nutrients and the formation of a more stable soil structure (Duchene et al., 2017; Bünemann et al., 2018). Although changes in total organic matter content are generally observed only after several years of application, increased plant biomass input is an important factor in the gradual improvement of soil health (Lal, 2015; Lehmann et al., 2020). Increased soil biological activity is closely linked to more intensive nutrient cycling. More diverse microbial communities participate more effectively in the decomposition of plant residues and mineralization of organic compounds, thereby increasing nutrient availability during the growing season (Duchene et al., 2017). Combinations of legumes and non-legumes are particularly important, as biological fixation of atmospheric nitrogen contributes to an increase in the total amount of available nitrogen in the production system and reduces the need for mineral fertilization (Hauggaard-Nielsen et al., 2001; Duchene et al., 2017). At the same time, different dynamics in nutrient uptake from different soil depths improve nutrient use efficiency and reduce losses through leaching and denitrification (Hauggaard-Nielsen and Jensen, 2005; Brooker et al., 2015). Intercropping also has a beneficial effect on soil physical properties. Diverse root systems contribute to the formation and stabilization of soil aggregates and may increase soil porosity and improve water infiltration and retention (Mapa, 1995; Xiao et al., 2026). Increased soil cover during the growing season reduces the negative impact of raindrops, limits crust formation and decreases surface runoff, thereby mitigating the risk of erosion (Gregar et al., 2024). Intercropping can also improve water use efficiency, although these effects depend on climatic conditions, soil properties and crop management (Liu et al., 2025). In combination with minimal tillage, these effects may further contribute to the preservation of soil structure and improved soil water management.

Intercropping can also have an important role in the preservation of soil organic carbon. Increased production of aboveground and belowground biomass provides greater organic inputs to the soil, contributing to the formation of different soil organic matter fractions (Cotrufo et al., 2013; Li et al., 2023). Although changes in total soil organic carbon stocks require long-term application of such systems, research shows that increased inputs of plant residues can stimulate the accumulation of more active carbon fractions involved in nutrient cycling and gradually contribute to the formation of more stable carbon forms associated with the soil mineral fraction. Thus, intercropping can contribute to the preservation of soil fertility and long-term carbon sequestration (Li et al., 2023). Intercropping also increases the efficiency of using available natural resources. The complementary use of light, water and nutrients can increase overall productivity compared to sole cropping (Li et al., 2014; Yu et al., 2015). The efficiency of intercropping systems is often assessed by the Land Equivalent Ratio (LER), with values greater than 1 indicating more efficient



use of production area compared to sole cropping (Willey, 1979). Numerous studies and meta-analyses confirm that properly selected combinations of plant species achieve such values, although the results depend on agroecological conditions and management practices (Yu et al., 2015; Martin-Guay et al., 2018). Increased plant diversity in intercropping systems can support the biological regulation of pests, diseases and weeds by creating favorable conditions for beneficial organisms and limiting the spread of harmful organisms (Beillouin et al., 2019; Tamburini et al., 2020). Through the interaction of physical, chemical and biological processes, intercropping contributes to soil health, more efficient use of natural resources and greater resilience of agroecosystems (Glaze-Corcoran et al., 2020).

Intercropping as a component of more climate-resilient agroecosystems

Intercropping can improve the resilience of production systems by increasing the functional diversity of plant communities (Glaze-Corcoran et al., 2020; Burgess et al., 2022). Different plant species respond differently to changes in environmental conditions, which is why intercropping often achieves more stable yields in years marked by adverse weather conditions (Martin-Guay et al., 2018; Burgess et al., 2022). The complementary use of water, nutrients and light allows more efficient use of available resources during the growing season, especially in periodic droughts conditions, when different root system depths enable better water use from different soil depths (Hauggaard-Nielsen and Jensen, 2005; Brooker et al., 2015; Liu et al., 2025). Intercropping contributes to climate change adaptation primarily by improving the processes that determine soil health (Glaze-Corcoran et al., 2020; Burgess et al., 2022). It can also contribute to climate change mitigation by increasing plant biomass and organic matter inputs to the soil. The use of legumes can additionally reduce the dependence on mineral nitrogen fertilizers, while greater organic inputs may support the long-term maintenance of soil organic carbon stocks (Li et al., 2023; Duchene et al., 2017).

The effects of intercropping on the resilience of production systems depend on agroecological conditions and management practices (Brooker et al., 2015; Burgess et al., 2022). Therefore, the selection of plant species and cultivation practices should take into account climatic conditions, soil type and production goals. Adaptation to local conditions is one of the key factors for the successful application of intercropping in modern agriculture.

Limitations of application and future perspectives

Despite its numerous advantages, the wider application of intercropping in agricultural production is still limited by technological and economic factors (Brooker et al., 2015; Glaze-Corcoran et al., 2020). Successful planning of such production systems requires an understanding of the plant species interaction, resource requirements and growth dynamics, as well as the adjustment of agrotechnical measures during the growing season (Brooker et al., 2015). Future research should be focused on the development of production systems adapted to different agroecological conditions and on a better understanding of the long-term changes that intercropping causes in the soil. Long term experiments that allow monitoring of changes in soil health, nutrient cycling and the efficiency of natural resource use are particularly important (Beillouin et al., 2019; Glaze-Corcoran et al., 2020). At the same time, it is necessary to explore the synergistic effects of intercropping in combination with other agroecological practices, such as conservation tillage, cover crops, and diverse crop rotation (Beillouin et al., 2019; Tamburini et al., 2020).



Conclusion

Intercropping is an agroecological practice that naturally fits into the principles of conservation agriculture and contributes to more sustainable management of production systems. By increasing plant diversity, it enables more efficient use of natural resources, improves the physical, chemical and biological soil properties and contributes to preserving soil health. At the same time, it promotes more efficient nutrient cycling, increases production stability and contributes to the resilience of agroecosystems to climate change.

Although the effectiveness of intercropping depends on the choice of plant species, agroecological conditions and management methods, current knowledge confirms its significant potential as a component of sustainable agricultural production. Future research should focus on long-term trials and the development of production systems adapted to different production conditions in order to fully exploit the benefits of intercropping in preserving soil health, using natural resources more efficiently, and adapting agriculture to climate change.

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Efficiency and kinetics of phenol degradation during vermicomposting of olive pomace and cattle manure

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Abstract

The aim of this research was to evaluate the dynamics of organic matter humification and detoxification efficiency during the pilot-scale vermicomposting of olive pomace (OP) and cattle manure (CM) mixtures. Three experimental matrices were monitored: T1 (30% OP + 70% CM; control), T2 (40% OP + 60% CM + supplemented with 2% (w/w) of a liquid commercial organic amendment of Vigosol, organic conditioning agent), and T3 (50% OP + 50% CM + supplemented with 2% (w/w) of Vigosol and 10% (w/w) of household organic waste as an additional co-substrate), across initial, active, and final phases of the vermicomposting process. A two-way ANOVA and Tukey's HSD test were used for statistical analysis. The composting phase was the dominant factor driving substrate stabilization ($p < 0.05$). Electrical conductivity dropped sharply in T1 from 3573.3 to 514.7 $\mu\text{S}/\text{cm}$ in the active phase ($p < 0.001$). Humification was confirmed by an increase in humus from 4.46–5.51% to 13.00–14.95% in the final phase ($p < 0.001$). Total phenols decreased by 42.4–59.9%, indicating high detoxification. Vermicomposting proved highly effective for agro-industrial waste transformation.

Key words: agro-industrial waste, bioconversion, detoxification, humification, organic amendment

Introduction

The processing of agricultural by-products represents one of the most critical environmental challenges in the Mediterranean region. Olive pomace (OP), the primary solid waste generated by the olive oil extraction industry, is produced in massive quantities within a short seasonal timeframe (Roig et al., 2006). Raw OP is characterized by low pH, high phytotoxicity, and organic resistance, primarily due to the elevated concentration of phytotoxic phenolic compounds and lipids, which severely limit its direct disposal or application to agricultural soils (Plaza et al., 2008; Contreras-Angulo et al., 2025). Concurrently, the sustainable management of livestock residues, such as cattle manure (CM), requires cost-effective and environmentally friendly stabilization methods to minimize nutrient loss and microbial risks (Atiyeh et al., 2000). Vermicomposting, a bio-oxidative process mediated by the joint action of earthworms and microorganisms, has emerged as a highly efficient biotechnology for converting hazardous agro-industrial wastes into nutrient-rich, stable biofertilizers (Ndegwa and Thompson, 2001). Earthworms significantly alter the microbial community structure, enhancing the mineralization of organic matrices and accelerating the humification process (Aira et al., 2007). Moreover, recent advances have highlighted that the co-vermicomposting of olive mill wastes with nitrogen-rich animal manures and specific organic amendments can drastically decrease total phenol content, neutralize acidity, and overcome inherent process limitations (Tomati et al., 2000). The application of external organic additives further optimizes the optimization of biostabilization and reduces potential



matrix toxicity (Marín et al., 2018). Despite the growing literature on co-composting, precise evaluations of how individual factors (such as the specific substrate mixture and the chronological process phase) interact to dictate nutrient retention and chemical kinetics remain scarce. Therefore, the main objective of this study was to evaluate the humification dynamics and phenol degradation efficiency during the pilot-scale vermicomposting of OP and CM under different organic amendment conditions. Utilizing a robust two-way analysis of variance (ANOVA), this paper quantifies the specific and interactive effects of treatment formulations and process phases on physicochemical properties, providing novel insights into tailored waste valorization pathways.

Material and Methods

The pilot-scale vermicomposting experiment was conducted using different combinations of agro-industrial waste matrices: olive pomace (OP) and cattle manure (CM). Prior to mixing, raw materials were characterized, revealing contrasting chemical profiles: CM possessed a high pH and calcium-rich carbonate buffering, while raw OP was highly acidic and rich in phytotoxic phenolic compounds. Three distinct experimental treatments (matrices) were established based on weight ratios: T1: 30% OP + 70% CM (acting as the control matrix); T2: 40% OP + 60% CM, supplemented with 2% (w/w) of a liquid commercial organic amendment (Vigosol, organic conditioning agent) calculated based on the total mass of the mixture; T3: 50% OP + 50% CM, supplemented with 2% (w/w) of Vigosol and 10% (w/w) of household organic waste as an additional co-substrate. For treatments T2 and T3, a 10-day stabilization pre-treatment was performed prior to the introduction of earthworms (*Eisenia fetida*). The pilot-scale vermicomposting experiment was initiated on September 15, 2025, starting with a 10-day stabilization pre-treatment. Following this pre-treatment, earthworms (*Eisenia fetida*) were introduced on September 25, 2025, to begin the active bioconversion process. The vermicomposting and maturation process was systematically monitored across three chronological stages (Initial, Active, and Final Maturation), concluding after a total of 160 days on February 20, 2026. This extended timeframe ensured thorough stabilization of the organic matrix and complete maturation of the final vermicompost. Physicochemical parameters and nutrient dynamics were monitored throughout the phases. Substrate acidity was determined via pH in H₂O and 1M KCl (BAS ISO 10390:2009 v/v 1:5). Soluble salt concentrations were tracked through electrical conductivity (EC, $\mu\text{S}/\text{cm}$), total dissolved solids (TDS, mg/L), and salinity (g/L) by HACH semsion5 in a 1:2 (w/v) ratio. Nutritional and humification indicators included total Nitrogen (N, % Kjeldahl method BAS ISO 11261: 2010), physiologically active phosphorus (P₂O₅) and potassium (K₂O) (AL-method Egner-Riehm-Domingu), humus (%) determined by the Kotzmann method, and carbonates (%) by Scheibler's calcimeter. Total phenolic compounds were extracted and quantified by Folin-Ciocalteu reagent method to evaluate substrate detoxification efficiency. All experimental treatments were performed in triplicate. The obtained data were subjected to statistical analysis using a robust two-way analysis of variance (ANOVA) to evaluate the main effects of individual factors (Treatment and Phase) as well as their interactive effects (Treatment $\times$ Phase). Post-hoc separation of means was performed using Tukey's Honest Significant Difference (HSD) test at a confidence level of $p < 0.05$. Statistical computations were executed using R software.

Results and Discussion

Table 1 presents the results of the two-way analysis of variance (ANOVA) for substrate acidity parameters (pH in H₂O and KCl) and soluble salt parameters (EC, TDS, salinity), while the corresponding mean values and Tukey's HSD grouping are shown in Table 2. The two-way



ANOVA results indicate that the applied treatment factor has no statistically significant effect on the changes in pH values measured in H₂O ($p = 0.86$) or the pH values measured in KCl ($p = 0.39$). Furthermore, the Treatment $\times$ Phase interaction did not show statistical significance ($p > 0.05$), implying that all examined compost variants behaved similarly over the observed period. On the other hand, the composting phase factor had a statistically significant effect on both pH in H₂O ($p = 0.05$) and pH in KCl ($p = 0.01$). Generally, a slight increase in pH values was observed during the active phase compared to the initial phase, most visibly in Treatment 3, where the value rose from 7.53 to 8.08, followed by a slight decline and stabilization in the final phase. Nevertheless, the post-hoc Tukey HSD test classified all combinations of treatments and phases into the same homogeneous group "a", indicating that the fluctuations in substrate acidity were subtle, even though the global trend of change across the phases was recognized as statistically significant. The increase in pH during the active phase can be attributed to the intensive decomposition of organic acids and the release of ammonia driven by earthworm activity and the associated microbial biomass (Atiyeh et al., 2000), while the subsequent stabilization in the final phase suggests the gradual maturation and humification of the vermicompost (He et al., 1992). In contrast to acidity, the parameters describing the concentration of soluble salts (EC, TDS, and salinity) showed an exceptionally high statistical significance solely under the influence of the composting phase factor ($p < 0.001$), while the effect of the treatment itself and the Treatment $\times$ Phase interaction were not statistically significant ($p > 0.05$). The post-hoc Tukey HSD test clearly separates the vermicomposting phases into distinct homogeneous groups, with the initial phase (phase zero) recording by far the highest values of (EC), (TDS), and salinity across all treatments. For instance, Treatment 1 in the initial phase recorded an EC value of 3573.33 $\mu\text{S}/\text{cm}$, a TDS of 1850.33 mg/L , and a salinity of 1.43 g/L , placing it in groups "a" and "ab". Upon entering the active phase, a dramatic and statistically significant drop in these values was observed in all variants, which was most pronounced in Treatment 1, where EC decreased to a minimum of 514.67 $\mu\text{S}/\text{cm}$, group "c". In the final phase, a slight but statistically non-significant increase or maintenance of low values compared to the active phase was recorded, causing these combinations to mostly share the transitional groups "bc" and "abc". This sharp decline in EC, TDS, and salinity from the initial to the active phase indicates intense leaching processes, the binding of free ions into the microbial biomass, or their precipitation into stable insoluble forms during the initial, most active phase of earthworm action (Singh et al., 2018), while the subsequent stabilization in the final phase serves as a direct indicator of reaching the maturity and stability of the obtained vermicompost (Gómez-Brandón et al., 2013).

Table 1. Two-way ANOVA results ($\text{Pr}(> F)$ values) for the monitored parameters

Parameter	Treatment ($\text{Pr}(> F)$)	Phase ($\text{Pr}(> F)$)	Interaction T:Ph ($\text{Pr}(> F)$)
pH in H ₂ O	0.8650	0.0486 *	0.8498
pH in KCl	0.3968	0.0106 *	0.8444
EC	0.9790	< 0.001 ***	0.2440
TDS	0.8750	< 0.001 ***	0.1450
Salinity	0.1890	< 0.001 ***	0.1930



Table 2. Mean values and Tukey's HSD post-hoc grouping for the monitored parameters

Parameter	T1: Initial	T1: Active	T1: Final	T2: Initial	T2: Active	T2: Final	T3: Initial	T3: Active	T3: Final
pH	7.53 ^a	7.96 ^a	7.94 ^a	7.51 ^a	7.98 ^a	7.66 ^a	7.53 ^a	8.08 ^a	7.58 ^a
KCl	7.12 ^a	7.42 ^a	7.39 ^a	7.18 ^a	7.53 ^a	7.24 ^a	7.02 ^a	7.40 ^a	7.15 ^a
EC (μS/cm)	3573.3 ^a	514.7 ^c	766.7 ^{bc}	2700 ^{ab}	954.3 ^{bc}	1329 ^{bc}	2580 ^{abc}	899.7 ^{bc}	1583.7 ^{abc}
TDS (mg/L)	1850.3 ^a	249.3 ^c	374.3 ^{bc}	1375 ^{ab}	468 ^{bc}	663.7 ^{bc}	1309 ^{abc}	441.0 ^{bc}	978.7 ^{abc}
Salinity (g/L)	1.43 ^{ab}	0.23 ^c	0.40 ^{bc}	1.97 ^a	0.47 ^{bc}	0.63 ^{bc}	1.23 ^{abc}	0.40 ^{bc}	0.97 ^{abc}

Different letters within the same column indicate statistically significant differences at $p < 0.05$.

The two-way ANOVA and Tukey's HSD results for the remaining macroelements (P_2O_5 , K_2O , N), organic matter indicators (humus and carbonates), and total phenols are compiled in Tables 3 and 4.

Table 3. Two-way ANOVA results for nutrients and organic parameters

Parameter	Treatment (Pr(>F))	Phase (Pr(>F))	Interaction T:Ph (Pr(>F))
P_2O_5	0.0709	0.4182	0.5818
K_2O	0.5180	0.00016***	0.0302*
N (Nitrogen)	0.00093 ***	0.9020	0.1655
Humus	0.0488 *	< 0.001 ***	0.2378
Carbonates	0.2041	0.00837**	0.0797
Total phenols	0.0155 *	< 0.001***	0.7698

Table 4. Mean values and Tukey's HSD for nutrients and organic parameters

Parameter	T1: Init	T1: Act	T1: Fin	T2: Init	T2: Act	T2: Fin	T3: Init	T3: Act	T3: Fin
P_2O_5 (%)	0.42 ^a	0.29 ^a	0.32 ^a	0.41 ^a	0.43 ^a	0.37 ^a	0.31 ^a	0.28 ^a	0.31 ^a
K_2O (%)	1.01 ^a	0.28 ^b	0.34 ^{ab}	0.99 ^a	0.26 ^b	0.38 ^{ab}	0.70 ^{ab}	0.34 ^{ab}	0.93 ^{ab}
N (%)	2.60 ^{ab}	2.32 ^{ab}	2.09 ^b	2.74 ^{ab}	2.94 ^a	2.95 ^a	2.67 ^{ab}	2.71 ^{ab}	2.80 ^{ab}
Humus (%)	4.46 ^b	10.93 ^a	13.0 ^a	5.07 ^b	14.95 ^a	13.41 ^a	5.51 ^b	13.15 ^a	14.95 ^a
Carbonates (%)	5.20 ^b	6.51 ^{ab}	8.26 ^{ab}	5.53 ^b	6.64 ^{ab}	7.53 ^{ab}	5.67 ^b	10.63 ^a	7.22 ^{ab}
Phenols (mg/kg)	45.18 ^{ab}	22.59 ^{bc}	19.07 ^c	59.27 ^a	33.24 ^{bc}	29.23 ^{bc}	57.44 ^a	37.20 ^{abc}	23.01 ^{bc}

Regarding macronutrients, the applied treatment showed a highly significant effect only on total Nitrogen content ($p = 0.00093$), where Treatment 2 maintained the highest overall values throughout the process (reaching 2.95% in the final phase, group "a"). Conversely, the composting phase was the dominant factor influencing K_2O dynamics ($p = 0.00016$), driving a general decrease from the initial phase to the active and final stages across the variants. Interestingly, K_2O was the only parameter exhibiting a significant Treatment $\times$ Phase interaction ($p = 0.0302$), demonstrating that the rate of potassium stabilization varied slightly depending on the compost matrix. Phosphorus (P_2O_5) levels remained statistically unaffected by any of the investigated factors ($p > 0.05$), with all combinations remaining within a single homogeneous group "a". Organic matter decomposition and stabilization were heavily reflected through humus and carbonate dynamics, both being highly significantly influenced by the composting phase ($p < 0.001$ and $p < 0.01$, respectively). Humus content significantly increased from the initial phase (ranging from 4.46% to 5.51%, group "b") to the active and final phases (exceeding 13% in most treatments, group "a"), confirming intense humification driven by earthworm and microbial activity. Similarly, carbonates showed a steady upward trend toward the final phase, which is characteristic of organic mass reduction and mineralization (Edwards et al., 2011). Total phenolic compounds were significantly affected by both individual factors: Treatment ($p = 0.0155$) and Phase ($p < 0.001$), while their



interaction was non-significant ($p = 0.7698$). The highest initial concentration of phenols was detected in Treatment 2 (59.27 mg/kg, group "a"), followed by a sharp, statistically significant decline across all treatments by the final phase (dropping to as low as 19.07 mg/kg in Treatment 1, group "c"). This significant reduction in total phenols highlights the efficiency of the

vermicomposting process in detoxifying the substrate and eliminating potential phytotoxic compounds. Phenol degradation during vermicomposting relies on the synergy between earthworms (*Eisenia fetida*) and microorganisms. Earthworms physically fragment the tough olive pomace, increasing the surface area for microbial colonization. During gut transit, earthworm mucus stimulates phenol-tolerant bacteria (such as *Pseudomonas* and *Bacillus* sp.), which are then dispersed throughout the matrix. These microbes secrete extracellular oxidative enzymes (laccases, manganese peroxidases, and polyphenol oxidases) that cleave phytotoxic aromatic rings. The resulting aliphatic intermediates are either mineralized to CO₂ or incorporated into stable humic and fulvic acids (Aira et al., 2007; Plaza et al., 2008). This combined enzymatic cleavage and humic polymerization permanently detoxifies the matrix for safe agricultural use.

Conclusion

Based on the two-way ANOVA and post-hoc analysis of the monitored parameters during the vermicomposting process, several key conclusions can be drawn: The composting phase was the dominant factor driving the stabilization of the substrate, causing a highly significant reduction in EC, TDS, salinity, and total phenolic compounds, which directly indicates efficient detoxification and reduction of potential phytotoxicity. Substrate humification progressed successfully across all treatments, as evidenced by a substantial increase in humus and carbonate content from the initial to the final phase. The applied organic waste treatments did not significantly alter the overall pH matrix or phosphorus dynamics, but Treatment 2 proved superior in retaining total Nitrogen throughout the process. A statistically significant interaction between treatment and phase was unique to K₂O dynamics, suggesting that potassium transformation pathways are slightly sensitive to the initial compost composition. Overall, the process yielded a stable, mature, and nutrient-rich vermicompost.

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Utjecaj primjene korisnih mikroorganizama na broj mikroorganizama u tlu u nasadima vinograda

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Sažetak

Istraživanje je provedeno na tri tipa tla (crvenica, eutrično smeđe tlo, lesivirano tlo) u nasadima vinograda. U rujnu 2024. i 2025. godine uzeti su uzorci tla radi određivanja kemijskih i mikrobioloških svojstava tla. Rezidba je obavljena tijekom ožujka na sva tri lokaliteta, te su organski ostaci usitnjeni pomoću malčera. Usitnjeni organski ostaci poprskani su mikrobiološkim pripravcima Vitality-FAZOS (*Trichoderma* spp.), Super Green-FAZOS (*Bacillus megaterium*, *Bacillus subtilis*, *Azotobacter chroococcum*, *Azospirillum brasilense*) i Protect-FAZOS (*Bacillus thuringiensis*, *Beauveria bassiana*), te su pomoću kultivatora unešeni u tlo. Broj pojedinačnih vrsta mikroorganizama u preparatima iznosio od 8×10^9 – 4×10^{10} cfu/ml. Rezultati istraživanja ukazuju da u varijantama gdje nisu primijenjeni biopreparati nije bilo razlike između kemijskih svojstava tla 2024. i 2025. godine. Međutim, kod tretiranih varijanata, kod sva tri tipa tla, utvrđeno je relativno povećanje P_2O_5 (mg/ 100 g tla) od 13,33 – 17,43 %. Kod sva tri tipa tla, kod tretiranih varijanata, broj svih istraživanih grupa i vrsta mikroorganizama bio je veći (ukupan broj bakterija 5,26 - 11,15 %; ukupan broj gljiva 6,80 – 12,6 %; ukupan broj aktinomiceta 4,67 – 16,31 %; *Azotobacter* spp. 16,67 – 20,17 %; *Trichoderma* spp. 29, 91 – 34,32 %; *Bacillus* spp. 14,10 – 28,35 %).

Ključne riječi: mikrobiološki preparati, vinova loza, organski ostaci, koncentracija mikroorganizama

Uvod

Strateški Zeleni plan EU ima za cilj promicanje održive poljoprivredne proizvodnje kako bi se osigurala sigurnost hrane i postigla klimatska neutralnost (Havryliuk et al., 2022, Nazarov et al., 2021). To uključuje reduciranje kemijskih pesticida i promicanje organskih poljoprivrednih praksi. Iz tog razloga koriste se i mikrobiološki pripravci koji povećaju poljoprivrednu produktivnost. Mikrobiološki preparati koriste se za stimuliranje razgradnje organskih ostataka i mineralizaciju humusa, kao alternativa kemijskim pesticidima, te kao stimulatori rasta (Fenibo et al., 2022, Narwade et al., 2023, Parajuli et al., 2022, Rowinska et al., 2024). Ovi preparati, tzv. Biognojiva, su jedan od najboljih načina za povećanje ili održavanje trenutne razine proizvodnje uz osiguranje stabilnosti okoliša. Sadrže vrste roda *Azospirillum*, *Azotobacter*, *Rhizobium*, *Pseudomonas*, *Bacillus* (Divya et al., 2023, Upadhyay et al., 2021, Vishal et al., 2023). Navedeni preparati poboljšavaju kvalitetu tla i podržavaju rast biljaka kao rezultat sinteze regulatora rasta, biokontrola fitopatogena ili indukcije imuniteta tijekom stresnih uvjeta. Također mogu poboljšati apsorpciju teško dostupnih elemenata zbog svoje sposobnosti otapanja fosfora, kalija i cinka (Kumar et al., 2022; Singh et al., 2017). Mikroorganizmi imaju fungicidno, baktericidno, virocidno i insekticidno djelovanje, te se sve više koriste biopreparati koji sadrže sljedeće mikroorganizme: *Bacillus*



thuringiensis, *Metarhizium anisopliae*, *Beauveria bassiana*, *Trichoderma* spp., *Bacillus* spp. (Chakraborty et al., 2023., Marwal et al., 2022, Parajuli et al., Steglińska et al., 2022). U razgradnji žetvenih ostataka, kao i mineralizaciji humusa najznačajniju ulogu imaju mikroorganizmi. Razgradnja žetvenih ostataka ima ključnu ulogu u kruženju hranjivih tvari i plodnosti tla, što u konačnici podržava zdrav rast biljaka i visoku poljoprivrednu produktivnost (Bunas et al., 2022, Pržulj et al., 2022). Procesi razgradnje oslobađaju hranjive tvari iz ostataka, čineći ih dostupnima za unos biljaka i doprinoseći ukupnom sadržaju hranjivih tvari u tlu. Razgradnja pomaže u održavanju razine organske tvari u tlu (Cayuela et al., 2009, Singh i Sharma, 2020). Također utječe na strukturu tla, zadržavanje vode i cjelokupnu mikrobnu zajednicu, što sve utječe na zdravlje tla i funkcioniranje ekosustava (Ramteke et al., 2018). U jednogodišnjim istraživanjima cilj je bio prikupiti informacije o djelovanju mikrobioloških preparata na broj mikroorganizama u tlu, kako bi nakon toga proširila i detaljizirala istraživanja na utjecaj mikrobioloških preparata na elemente prinosa i kvalitete proizvoda, uključujući i sadržaj mikroelemenata u biljnoj masi i plodovima.

Material i metode

Istraživanje je provedeno po split – blok shemi u 4 ponavljanja na tri tipa tla; Crvenica (Splitsko-dalmatinska županija), Eutrično smeđe tlo (Osječko-baranjska županija), Lesivirano tlo (Požeško-slavonska županija) u nasadima vinograda. Obuhvaćeno je šest varijanti; tip tla - A.1. Crvenica, A.2. Eutrično smeđe tlo, A.3. Lesivirano tlo i tretman mikrobiološkim preparatima – B.1. kontrola, B.2. tretirano mikrobiološkim preparatima. U rujnu 2024. i 2025. godine uzeti su uzorci tla (po 4 sa svake varijante na svakom tipu tla) radi određivanja kemijskih i mikrobioloških svojstava tla na dubini 0 – 30 cm.

Kemijska svojstva određena su sljedećim metodama; pH u vodi i KCl (ISO 03390), sadržaj organske tvari (SOM) metodom prema standardu (ISO 14235), sadržaj P_2O_5 i K_2O AL metodom (Egner et al., 1960).

Ukupni broj bakterija određen je na Hranjivom agaru, ukupni broj gljiva na Krumpirovom dekstroznom agaru (PDA), ukupni broj aktinomiceta na Škrobno-amonijačnom agaru, broj *Azotobacter* spp. na Ashbyjevoj podlozi, *Trichoderma* spp. na Malt extract peptone agaru, *Bacillus* spp. na Tryptone soya agaru. Broj mikroorganizama određen je metodom serijskih razrjeđenja.

Rezidba je obavljena tijekom ožujka na sva tri lokaliteta, te su organski ostaci usitnjeni pomoću malčera. Usitnjeni organski ostaci tretirani su pomoću prskalice mikrobiološkim preparatima Vitality-FAZOS (*Trichoderma* spp.), Super Green-FAZOS (*Bacillus megaterium*, *Bacillus subtilis*, *Azotobacter chroococcum*, *Azospirillum brasilense*) i Protect-FAZOS (*Bacillus thuringiensis*, *Beauveria bassiana*), te su pomoću kultivatora unešeni u tlo. Broj pojedinačnih vrsta mikroorganizama u preparatima iznosila od 8×10^9 – 4×10^{10} cfu/ml.

Rezultati i rasprava

Početkom rujna 2024. godine uz pomoć sonde uzeti su uzorci za kemijsku i mikrobiološku analizu sa sva tri tipa tla (Tablica 1., Tablica 2.). Prema rezultatima kemijskih analiza najbolja svojstva imalo je eutrično smeđe tlo, izuzev sadržaja K_2O koji je bio viši za 16,32 % kod crvenice. Sukladno kemijskim svojstvima tla, u prvom redu pH vrijednosti i sadržaju humusa, najbolja mikrobiološka svojstva također su utvrđena na eutričnom smeđem tlu. Istraživanja brojnih autora su pokazala da se povećanjem sadržaja organske tvari u tlu povećava i mikrobiološka aktivnost i obratno (Chertov et al., 2018, Hellwig et al., 2018, Zhou et al., 2002).



Tablica 1. Kemijska svojstva tla u 2024. godini

Table 1. Soil chemical properties in 2024

Ispitivana svojstva tla <i>Soil properties</i>	Tip tla <i>Soil type</i>		
Oranični sloj <i>Plowing layer</i> (0 – 30 cm)	Crvenica <i>Terra rossa</i>	Eutrično smeđe <i>Eutric cambisol</i>	Lesivirano <i>Luvisol</i>
pH (H ₂ O)	6,32	6,81	6,08
pH (KCl)	5,67	6,02	5,37
Humus (%)	2,23	2,58	1,97
P ₂ O ₅ (mg/ 100 g tla)	20,12	23,70	18,35
K ₂ O (mg/ 100 g tla)	27,80	23,90	21,40

Tablica 2. Mikrobiološka svojstva tla u 2024. godini

Table 2. Microbiological properties of soil in 2024

Tip tla <i>Soil type</i>	(log cfu g ⁻¹)					
	Ukupne bakterije	Ukupne gljive	Ukupne aktinomicete	<i>Azotobacter</i> spp.	<i>Trichoderma</i> spp.	<i>Bacillus</i> spp.
Crvenica	9,69	5,96	5,28	3,65	3,21	4,26
Eutrično smeđe	10,03	4,80	6,08	4,07	3,49	4,70
Lesivirano	8,41	6,45	4,27	3,48	3,17	385

Početkom rujna 2025. godine ponovljeno je uzimanje uzoraka tla na svim tipovima tala u istraživanju, i to sa netretiranog dijela (kontrola), kao i dijela tretiranog biopreparatima. (Tablica 3. i Tablica 4.)

Tablica 3. Kemijska svojstva tla u 2025. godini

Table 3. Chemical properties of soil in 2025

Ispitivana svojstva tla <i>Soil properties</i>	Tip tla <i>Soil type</i>		
Oranični sloj <i>Plowing layer</i> (0 – 30 cm)	Crvenica <i>Terra rossa</i>	Eutrično smeđe <i>Eutric brown soil</i>	Lesivirano <i>Loess soil</i>
Kontrola/Control			
pH (H ₂ O)	6.28	6.76	5.80
pH (KCl)	5.60	5.97	5.21
Humus (%)	2.17	2.45	1.90
P ₂ O ₅ (mg/ 100 g tla)	19.46	23.56	17.85
K ₂ O (mg/ 100 g tla)	26.50	23.65	20.75
Tretirano biopreparatima/ Treated with microbial preparation			
pH (H ₂ O)	6.08	6.95	6.01
pH (KCl)	5.71	6.27	5.30
Humus (%)	2.27	2.50	1.88
P ₂ O ₅ (mg/ 100 g tla)	22.06	26.70	20.96
K ₂ O (mg/ 100 g tla)	28.00	23.10	21.40



Između kontrolne varijante i varijante tretirane mikrobiološkim preparatima (Tablica 3.), kada su u pitanju kemijska svojstva tla, najočitija razlika u sadržaju fosfora u tlu. Kod sva tri tipa tla došlo je do povećanja sadržaja P_2O_5 u tlu kod varijante tretirane mikrobiološkim preparatima u odnosu na kontrolnu varijantu (netretirano tlo). Kod Crvenice to povećanje iznosilo je 13,36 %, kod Eutrično smeđeg tla 13,33 %, te kod Lesiviranog tla 17,43 %. Za pretpostaviti je da je razlog tome unošenje bakterije *Bacillus megaterium* u tlo. Rezultati istraživanja brojnih autora pokazuju da primjenom bakterije *Bacillus megaterium* dolazi do značajnog povećanja fosfora u tlu jer bakterija svojim eskudatima „otapa kamene fosfate“ (Yingnan et al., 2021, Betül 2022, Bondar et al., 2024). U varijanti tretiranoj mikrobiološkim preparatima (Tablica 4.) utvrđen je porast broja svih ispitivanih mikroorganizama na sva tri tipa tla. Razgradnja organskih ostataka u tlu u prvom redu zavisi od mikrobiološke aktivnosti, a s druge strane, što je veća količina organskih ostataka to je i veća koncentracija mikroorganizama (Ramteke et al., 2018). Na eutričnom smeđem tlu, gdje je pH_{KCl} 6,27, također je došlo do povećanja broja benefitnih gljiva *Trichoderma* spp. (Blaya et al., 2013, Asghar et al., 2024). Iako su gljive acidofilni mikroorganizmi, *Trichoderma* spp. se razvija i do pH_{KCl} 6,80.

Tablica 4. Mikrobiološka svojstva tla u 2025. godini

Table 4. Microbiological properties of soil in 2025

Tip tla Soil type	(log cfu g ⁻¹)					
	Kontrola/Control					
	Ukupne bakterije	Ukupne gljive	Ukupne aktinomicete	<i>Azotobacter</i> spp.	<i>Trichoderma</i> spp.	<i>Bacillus</i> spp.
Crvenica	9,48	5,88	5,13	3,47	3,31	4,31
Eutrično smeđe	10,13	4,68	6,13	4,30	3,28	4,55
Lesivirano	8,52	6,38	4,09	3,48	3,38	3,76
Tretirano biopreparatima/ Treated with biopreparations						
Crvenica	10,06	6,28	5,37	4,17	4,30	4,95
Eutrično smeđe	11,26	5,91	7,13	5,20	4,38	5,84
Lesivirano	8,97	7,31	4,46	4,06	4,54	4,29

Zaključak

Na temelju dobivenih rezultata istraživanja možemo zaključiti da je na sva tri tipa tla između kontrolne varijante i varijante tretirane mikrobiološkim preparatima došlo do povećanja sadržaja fosfora u tlu od 13,33% do 17,43%. Također je u varijanti tretiranoj mikrobiološkim preparatima utvrđen je porast broja svih ispitivanih mikroorganizama na sva tri tipa tla.

Zahvala

Rad je rezultat istraživanja na projektu (INT: 77.03, ID 2104843) „AGRICMICROBALANCE - Primjena mikroorganizama za povećanje produktivnosti u voćarstvu i vinogradarstvu“ (Intervencija 77.03. Potpora za EIP operativne skupine iz SPZPP RH 2023. – 2027.).

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Impact of application of beneficial microorganisms on the number of microorganisms in soil in vineyard plants

Summary

The research was conducted on three soil types (red soil, eutric brown soil, and leached soil) in vineyard plantations. Soil samples to determine the chemical and microbiological properties of the soil were taken in September 2024 and 2025. Pruning was carried out during March at all three locations, and organic residues were shredded using a mulcher. The shredded organic residues were sprayed with microbiological preparations Vitality-FAZOS (*Trichoderma* spp.), Super Green-FAZOS (*Bacillus megaterium*, *Bacillus subtilis*, *Azotobacter chroococcum*, *Azospirillum brasilense*) and Protect-FAZOS (*Bacillus thuringiensis*, *Beauveria bassiana*), and were incorporated into the soil using a cultivator. The number of individual species of microorganisms in the preparations was from 8×10^9 – 4×10^{10} cfu/ml. The research results show that in variants where biopreparations were not used, there was no significant difference between the chemical properties of the soil in 2024 and 2025. However, in all three soil types in the treated varieties, an increase in P₂O₅ (mg/ 100 g soil) of 13.33 – 17.43% was obtained. In all three soil types, in treated varieties, the number of all investigated groups and types of microorganisms was higher (total number of bacteria 5.26 – 11.15%; total number of fungi 6.80 – 12.6%; total number of actinomycetes 4.67 – 16.31%; *Azotobacter* spp. 16.67 – 20.17%; *Trichoderma* spp. 29.91 – 34.32%; *Bacillus* spp. 14.10 – 28.35%).

Keyword: microbiological preparations, grapevine, organic residues, number of microorganisms



Edaphic factors shape oribatid mite communities in urban forest soils

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Abstract

Urban forest soils represent heterogeneous habitats where edaphic conditions are shaped by vegetation structure, management intensity and long-term anthropogenic influences. This study aimed to compare communities of oribatid mites across three contrasting urban forest sites in Slovakia and to evaluate how soil pH-values, soil water content and texture influence their abundance and species composition. Attention was paid to the role of these edaphic parameters in determining differences in community structure among urban forest habitats. Substantial differences among the studied sites were observed. The highest diversity and abundance of oribatid mites were recorded in Forest Park Bratislava (HPB), where favourable moisture conditions and a well-developed humus layer supported 37 species with a total abundance of 487.5 ind./dm³. In contrast, Forest Park Prievidza (FPP) exhibited extremely low oribatid occurrence, with only three individuals belonging to two species. This result reflects the combined limiting effects of low soil moisture and an unfavourable silt-to-sand ratio, which likely reduced soil porosity and microbial activity and consequently limited habitat suitability for soil microarthropods. The Forest Park Žilina (FPZ) supported 17 species with an abundance of 20.50 ind./dm³ despite lower moisture availability. The assemblage at this site was dominated by acid-tolerant taxa such as *Tectocephus* sp., *Oppiella* sp. and *Euzetes globulus*, indicating the strong selective role of soil acidity in structuring the community. The results indicate that soil moisture is the primary determinant of oribatid abundance and diversity, whereas soil pH is primarily a selective factor in strongly acidic environments. Soil texture further modifies habitat suitability by influencing pore structure, aeration and the mobility of soil fauna. Overall, the findings demonstrate that even within urban forest ecosystems, edaphic parameters consistently shape oribatid assemblages and differentiate stable, humus-rich habitats from sites affected by edaphic stress or degradation.

Key words: edaphic factors; oribatid mites; soil texture; soil moisture, urban forest

Introduction

Urban forest soils are highly heterogeneous environments shaped by both natural processes and anthropogenic influences (Yesilonis et al. 2022). Oribatid mites (Oribatida; Acarina) are among the most important groups of soil mesofauna, contributing to organic matter decomposition and nutrient cycling while serving as indicators of soil environmental conditions (Hågvar 2019). Because their occurrence is closely linked to soil properties, changes in soil pH, soil moisture, or soil texture may substantially alter community composition (Reeve et al. 2022). We hypothesized that soil texture influences the abundance and diversity of oribatid mites by modifying moisture



availability and microhabitat conditions. This study aimed to compare communities of oribatid mites across three contrasting urban forest sites in Slovakia and to evaluate how soil pH, moisture and texture influence their abundance and species composition.

Material and Methods

Three urban forest parks located in Slovakia were selected for this study: Horský Park Bratislava (HPB), Lesopark Prievidza (FPP), and Lesopark Žilina (FPZ). HPB is characterized by oak–hornbeam forest stands and represents the locality with vegetation most closely resembling a natural forest ecosystem. FPP consists mainly of mixed deciduous stands with admixtures of coniferous species and areas modified for recreational use. FPZ represents a mixed urban forest dominated by deciduous trees, with remnants of coniferous species from previous planting activities.

The study sites were each represented by five sampling points. Volumetric soil water content (VWC) was measured in situ using a portable Delta-T Devices moisture meter. Measurements were conducted during a single field campaign. Five replicate measurements were performed at each sampling point, and the mean VWC value was used to characterize each study site. Disturbed soil samples were collected in two sets. One set was immediately transferred to Tullgren photoelectors for extraction of soil fauna, while the second set was sieved through a 2-mm mesh and dried at 105 °C for soil analyses. Soil pH (H₂O) was determined potentiometrically in a 1:2.5 soil-to-water suspension. Particle-size distribution was analysed using the pipette method (Fiala et al. 1999), and soil texture classes were determined according to the standard soil texture triangle. Oribatid mites were extracted using the Berlese–Tullgren method (Tullgren 1918), preserved in 80% ethanol, and mounted in Liquido de Swan medium. Darkly pigmented specimens were cleared in 60% lactic acid before identification. Species were identified under a microscope at 300–675× magnification using standard taxonomic keys. Abundance was expressed as the number of individuals per dm³ of soil.

Results and Discussion

Soil conditions in the studied urban forests varied considerably in both chemical and physical properties, reflecting the combined effects of natural processes and anthropogenic disturbances. Despite the limited dispersal ability of oribatid mites, differences in species composition among localities were primarily associated with local soil and vegetation characteristics rather than geographic isolation. Such habitat-specific associations create a mosaic distribution of taxa adapted to environmental conditions (Erdmann et al. 2012). Consequently, changes in vegetation structure, litter accumulation, or soil properties may alter soil communities and affect nutrient cycling and ecosystem functioning in urban forests (Alvarez et al. 2020).

Urban forests provide important ecosystem services, including biodiversity conservation, carbon sequestration, and the regulation of soil, water and climate processes (Endreny 2018). Increasing urbanisation alters soil physicochemical conditions through compaction, vegetation changes and recreational disturbance, potentially affecting soil biota. Understanding how edaphic factors structure soil communities is therefore important for assessing ecological quality and guiding sustainable management of urban forest ecosystems.

Soil pH-values differed among the studied localities and were associated with differences in oribatid mite abundance and diversity. The lowest pH-values were recorded at FPZ, while HPB and FPP exhibited strongly and moderately acidic soils, respectively (Table 1). The highest abundance and species richness were found at HPB, whereas FPP supported only two species with



a total abundance of 5.0 individuals dm^{-3} . Differences in soil texture likely contributed to these patterns by modifying soil pore structure and microhabitat availability. The clay-rich soil at HPB likely provided a greater proportion of small, stable pores that retain moisture and create buffered microhabitats favourable for oribatid mites. In contrast, the coarser texture at FPP, characterized by a higher proportion of sand and lower clay content, likely reduced water retention and

accelerated soil drying, thereby limiting suitable refuges for soil mesofauna. The intermediate texture at FPZ may partly explain why this locality supported a moderate number of species despite relatively low soil moisture and strongly acidic soil pH.

Table 1. Environmental characteristics and oribatid mite communities of the three studied urban forest sites.

Site	VWC (%)	pH (H_2O)	Texture (sand/silt/clay, %)	Species richness	Abundance (ind. dm^{-3})	Dominant community type
HPB	38.30	5.16	12.80/31.80/55.40	37	487.5	Diverse forest assemblage
FPP	24.34	5.65	41.77/39.77/18.47	2	5.0	Stress-tolerant generalists
FPZ	24.90	4.66	30.24/57.28/12.47	17	20.5	Acid-tolerant assemblage

Table notes: HPB – Forest Park Bratislava (Horský park); FPP – Forest Park Prievidza; FPZ – Forest Park Žilina. Species richness is expressed as the number of species; abundance is expressed as individuals dm^{-3} .

Soil pH influences nutrient availability, microbial community structure, and litter decomposition processes, thereby indirectly affecting soil fauna (Lavelle et al. 1995). Although some species are adapted to acidic conditions, increasing acidity generally reduces community abundance and favours acid-tolerant taxa such as *Oppiella nova*, *Tectocephus velatus sarekensis*, and *Punctoribates punctum*. These species were recorded at both HPB and FPZ, however, soil pH alone did not explain the observed patterns. HPB exhibited the highest diversity and abundance despite its strongly acidic soil, suggesting that other factors, particularly soil moisture, moderated the effects of acidity. This finding supports previous observations that optimal soil pH promotes higher faunal abundance only when additional environmental constraints are absent (Hågvar 2019).

Conclusion

Oribatid mite communities in the studied urban forests differed markedly among localities, reflecting variation in soil physicochemical properties. The highest species richness and abundance were recorded at HPB, where favourable soil structure and high soil moisture provided suitable conditions for a diverse oribatid community. In contrast, FPP supported only a few highly tolerant species, likely due to the combined effects of low soil moisture, unfavourable soil texture, and soil compaction associated with intensive recreational use. FPZ represented a naturally acidic habitat dominated by acid-tolerant taxa, where community development appeared to be limited by low soil moisture and low clay content. Our results indicate that soil moisture is the primary factor shaping oribatid mite communities in urban forests, while soil pH acts mainly as a selective factor and soil texture influences the availability of suitable microhabitats. The pronounced environmental heterogeneity of urban forests creates a mosaic of habitats supporting different



species assemblages. Overall, the study highlights the importance of soil physicochemical properties, particularly soil moisture, in maintaining diverse and ecologically stable oribatid mite communities.

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Obrađivanje duše: etička dimenzija agronomije u svjetlu biblijskog nauka

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Sažetak

Članak predstavlja interdisciplinarnu analizu normativnog potencijala biblijske teologije zemlje za oblikovanje suvremene agrarne etike. Povezujući biblijske znanosti, ekoteologiju i socioekonomsku etiku, polazi se od teze da biblijski tekstovi nude koherentan etički okvir za moderne izazove agronomiji. Kritičkim vrednovanjem intenzivne industrijske poljoprivrede preispituje se njezina moralna legitimnost s naglaskom na održivosti i društvenoj pravednosti. Hermeneutička analiza tekstova iz Knjige Postanka, Levitskog zakonika i proročke literature pokazuje da biblijski koncept „odmora zemlje“ anticipira agroekološka načela regenerativne poljoprivrede. Jubilejsko biblijsko zakonodavstvo postavlja temelje agrarne reforme i prehrambene pravednosti, dok proročka kritika latifundijalizacije izravno upućuje na opasnosti suvremenih agrobiznisa. Istraživanje utvrđuje da biblijska agrarna etika nudi trajni sustav vrijednosti i jasne smjernice za održivu obradu tla. Takav pristup pruža prijeko potreban etički okvir za odgovorno upravljanje zemljištem i očuvanje prirodnih resursa u uvjetima globalne ekološke i klimatske krize.

Ključne riječi: biblijska agrarna etika; biblijska teologija zemlje; ekoteologija; održiva agronomija

Uvod

Agronomija se danas primarno definira kao primijenjena znanost usmjerena na optimizaciju produktivnosti agroekosustava kroz genetiku, agrotehniku i digitalne tehnologije (Thompson, 2017; Bašić i Tomić, 2021). Takvo poimanje reducira tlo na ekonomski čimbenik, dok ekološke i socijalne posljedice – poput degradacije tla i marginalizacije malih proizvođača – smatra sekundarnima (Zimdahl, 2012). Međutim, tlo je složeni živi sustav te neobnovljivi resurs (Bašić, 2013a; Cifrić, 2002) za koji čovjek snosi odgovornost (Leopold, 1949; Berry, 1977). Stoga agronomija mora proširiti interes na pitanja održivosti, pravednosti i morala (Thompson, 2010; Clough, 2012). Budući da su korijeni ekološke krize povezani s religijskim tumačenjem odnosa čovjeka i prirode (White, 1967), otvara se nužan prostor za teološko propitivanje etičkih pravila unutar agronomске znanosti (Rolston III, 1988; Balabanić, 2009; Thompson, 2017).

Ova etička pitanja u središtu su socijalnog nauka Katoličke Crkve (Tanjić, 2016). Kroz koncept integralne ekologije, ekonomska, ekološka i društvena kriza promatraju se kao isprepletene, što od agronomije zahtijeva etičko usmjerenje kako tehnički razvoj ne bi proizvodio nove nepravde (Benedikt XVI, 2009; Franjo, 2015). Suvremena degradacija okoliša zapravo reflektira moralnu krizu koja traži korjenitu promjenu modela upravljanja tлом (Franjo, 2023). U tom kontekstu, Biblija nudi jasnu antropološku i teološku viziju suodnosa čovjeka, tla i Boga (Davis, 2009; Wright, 2004).

U ovome članku donosimo pregled biblijske agrarne etike te ukazujemo na njezinu normativnu važnost za agronomiju pred izazovima klimatskih promjena i digitalizacije poljoprivrede putem umjetne inteligencije. Kroz pet tematskih cjelina utvrđujemo epistemološki odnos Biblije i



agronomije, analiziramo ključne tekstove, rekonstruiramo njihov dijalog te u završnom dijelu primjenjujemo biblijsku etiku kao putokaz za nove agrarne tehnologije.

Važnost biblijskog nauka za suvremenu agronomiju

Iako Biblija nije agronomski priručnik i ne sadrži suvremene spoznaje o pedologiji ili fiziologiji biljaka, njezine su knjige nastale unutar agrarnog društva. Cjelokupne institucije, pravni propisi i teologija tog vremena prožeti su čovjekovom ovisnošću o tlu. Biblijski su pisci bili sofisticirani promatrači zemljoradnje te su korištenje zemlje smatrali prvorazrednim moralnim i teološkim pitanjem (Davis, 2009). Zato biblijski tekstovi predstavljaju izvor „agrarne mudrosti“ i sistematske etike relevantne za današnji globalni prehrambeni sustav. Ove su upute usporedive s onim što agroekologija naziva agroekološkom svijesti (Altieri, 2018). Ujedno, istraživanja pokazuju da su najstarije biblijske predaje (Post 1–11) oblikovane upravo kroz iskustvo prijelaza na zemljoradnju i nastanak prvih agrarnih struktura (Levy, 2023).

Aktualnost ove etike počiva na sličnosti povijesnih kriza s izazovima modernih agronoma. Starozavjetno se društvo suočavalo s koncentracijom vlasništva, pretjeranom eksploatacijom tla i nepravednom raspodjelom prinosa (Brueggemann, 2002). Slično tome, suvremena agronomija danas djeluje usred degradacije tla, gubitka bioraznolikosti i klimatskih promjena (Altieri, 2018). Intenzivna monokultura bez brige o organskoj tvari vodi trajnom gubitku produktivnosti tla (Bašić, 2013b). Taj problem prepoznavamo i u proročkoj kritici neograničenog iskorištavanja, gdje zemlja "tuguje i vene" jer plodnost postaje sredstvo moralne izopačenosti (Hoš 4,1-3). Ova paralela nudi analošku sličnost između biblijskih uvida i modernih opažanja. Biblijski tekstovi ne daju tehnička rješenja, već upućuju na normativna ograničenja i pravednost – segmente koje suvremena agronomija u svojoj tehnokratskoj ograničenosti često zanemaruje (Bouma-Prediger, 2010; Pardon, 2017).

Ovo etičko pitanje postaje ključno i kod primjene umjetne inteligencije u poljoprivredi. Digitalizacija i precizna poljoprivreda mijenjaju opseg ljudskog djelovanja, otvarajući nove dileme o odgovornosti i pravednosti (Dutta et al., 2026; Arora et al., 2026). Tehnički napredak bez etičkog horizonta produbljuje jaz u moći između velikih korporacija i malih proizvođača (Zimdahl, 2012). Zbog toga biblijska etika upraviteljstva (stewardship), utemeljena na ograničenosti ljudske moći, poziva agronome da uspostave načela suprotna tehnokratskoj paradigmi (Deane-Drummond, 2019). Kako bi se ta važnost uočila, tekstove valja ispravno tumačiti unutar starozavjetnog agrarnog konteksta te prepoznati njihov doprinos suvremenoj agrarnoj etici.

Biblijski temelji agrarne etike

Izvešće o stvaranju (Post 1,26-28) koristi hebrejske glagole *radah*, *abad* i *shamar* kako bi definiralo čovjekovu ulogu. Čovjek je stvoren na sliku Božju i povjereno mu je „vladanje“ (*radah*) nad svijetom. Tumačenje da ovo ovlaštenje dopušta neograničenu eksploataciju potpuno je pogrešno. U starozavjetnom kontekstu, *radah* označava delegiranu kraljevsku službu. Ljudska vlast proizlazi iz Božje suverenosti, pa se čovjek prema stvorenjima mora ponašati onako kako bi to Bog činio (Fretheim, 2005; Wright, 2004). Čovjek je tek upravitelj, a Bog ostaje stvarni vlasnik zemlje.

To se još jasnije vidi u Post 2,15, gdje Bog postavlja čovjeka u vrt da ga obrađuje (*abad*) i čuva (*shamar*) – odnosno, da mu služi i da ga štiti (Wenham, 1987; Westermann, 1984). Glagol *abad* ovdje nije neutralan pojam za fizički rad, već izraz koji redovito označava službu Bogu i bogoslužni čin. Time poljoprivreda postaje oblik službe unutar Saveza, a ne puko iskorištavanje tla. Glagol *shamar* unosi u agronomiju dimenziju zaštite i pažnje. Čovjekov zadatak nadilazi proizvodnju hrane; on mora čuvati tlo, što podrazumijeva ograničenje intenziteta korištenja



(Joerstad, 2019). Ovaj pojam priznaje intrinzičnu vrijednost agroekosustava neovisno o ljudskoj koristi (Habel, 2000).

Sinteza ovih pojmova ocrtava antropologiju upraviteljstva. Čovjek je opunomoćeni upravitelj čija je vlast uvjetovana odgovornošću prema Bogu i tlu. Uništavanje dostojanstva tla radi sebičnih interesa u ovoj je paradigmi etički neprihvatljivo (Wright, 2004; Fretheim, 2005). Instrumentaliziranje tla i prehrambenog sustava isključivo radi povećanja proizvodnje, bez obzira na odnose među ljudima, drugim stvorenjima i Zemljom, također je teško pomiriti s ovom etičkom perspektivom (Wirzba, 2019).

U odredbama o odmoru tla i Jubileju biblijska agronomska etika dobiva institucionalni oblik. Levitski zakonik propisuje da tlo, poput čovjeka i životinja, ima pravo na subotnji počinak; svake sedme godine zemlja ostaje neobrađena (Lev 25,1-7). To nije agrotehnički savjet o plodored, već teološko pravilo. Budući da tlo pripada Bogu, obrađivač mora periodično zaustaviti eksploataciju (Milgrom, 2001). Ova odredba, povezana sa subotnjim odmorom (Izl 20,8-11), pokazuje da neprekidna produktivnost nije apsolutna vrijednost, već je podređena granicama stvorenoga poretka (Wenham, 2004; Bašić, 1998).

Odredbe o Jubileju (Lev 25,8-55) nalažu da se svake pedesete godine zemljište vrati izvornim obiteljima, što sprječava trajnu koncentraciju posjeda (Douglas, 1999). Jubilej služi kao pravno-institucionalno ograničenje logike neograničenoga rasta. U suvremenoj agrarnoj etici ove odredbe odgovaraju potrebi zaustavljanja grabeža za zemljom (*land grabbing*) i njezina iskorištavanja na štetu budućih generacija (Altieri, 2018; Thompson, 2017).

Zakonodavstvo o pabirčenju (Lev 19,9-10; Dt 24,19-22) nalaže ostavljanje plodova na rubovima polja za siromašne i strance. To nije milostinja, već zakonsko pravo na hranu. Ove odredbe odgovaraju suvremenom konceptu prehrambene pravednosti, gdje se pristup hrani tretira kao temeljno pravo, a ne kao dobrovoljna solidarnost (Finn, 2013).

Koncentracija zemljišta u vlasništvu pojedinaca velika je tema proročkih spisa. Izaija i Mihej oštro kritiziraju one koji polja otimaju i gomilaju posjede (Iz 5,8; Mih 2,1-2). Ova kritika proizlazi iz teologije zemlje kao dara (Brueggemann, 2002). Kada zemlja postane predmet neograničene akumulacije, narušava se njezin smisao. U starozavjetnoj ekonomskoj etici, nepravda nanosena otimanjem posjeda nije samo socijalni prijestup, već moralni promašaj koji uništava i narod i tlo (Pardon, 2014, 2017).

Biblijska teologija tla i suvremena agrarna etika

Pri interpretaciji biblijskih principa važno je znati da starozavjetni tekstovi ne propisuju izravno agroekološke tehnike. Tumačenje počiva na analogiji, a ne na doslovnom prijenosu. Biblijski tekst nudi teološku gramatiku odnosa prema tlu. Zato u njemu ne smijemo tražiti tehničke propise, već etičke upute trebamo prevesti u suvremeni ekološki i agronomski rječnik.

Starozavjetna predaja ne prikazuje zemlju kao puku pasivnu materiju, nego joj u stvaranju pripisuje aktivnu ulogu. Zemlja „izvodi“ bilje i drveće (Post 1,11–12), čime sudjeluje u ostvarivanju Božjom riječju uspostavljenoga poretka stvaranja (Westermann, 1984). Bog stoga ne djeluje samo na zemlju nego i kroz njezinu vlastitu plodnost i sposobnost rađanja (Fretheim, 2005). Zemlja je tako uključena u odnos između Boga, čovjeka i ostalih stvorenja, a ne predstavlja tek neutralni objekt ljudske uporabe. Zemlja je dio Božjeg stvaranja i prostora u kojem se ostvaruje Božji odnos s čovjekom, dok je čovjek pozvan primiti je i koristiti unutar granica koje postavlja Bog (von Rad, 1962). Ta relacijska ontologija utemeljuje čovjekovu odgovornost. Zemlja kao dar poziva na zahvalnost, dok zemlja kao posjed predstavlja kušnju i vodi prema neograničenom raspolaganju (Brueggemann, 2002; Pardon, 2014). Dok industrijska poljoprivreda tretira tlo samo



kao proizvodni input, agroekologija ga vidi kao živi sustav s regenerativnim kapacitetom. Time je idejno puno bliža biblijskoj kategoriji darovanosti (Altieri, 2018; Thompson, 2017).

Odgovornost za tlo proizlazi iz koncepta upravljanja. Ta se obveza očituje kroz konkretno polaganje računa vlasniku. Upravitelj će kad-tad odgovarati za postupanje s povjerenim dobrom (Mt 25,14-30; Lk 19,11-27; Rim 14,12). Ovo biblijsko poimanje usklađeno je sa suvremenim ekonomskim konceptom transparentnosti, koji od proizvođača i institucija zahtijeva jasan obračun učinaka njihova djelovanja na tlo (Thompson, 2017).

Pravednost povezuje ekološku i socijalnu dimenziju ove etike te naznačuje principe integralne ekologije. Briga za tlo i briga za zajednicu neodvojive su. Degradacija tla uvijek prati propadanje ruralnih sredina i socijalnu nepravdu prema radnicima (Berry, 1977). Ova se teza oslanja na proročku kritiku gomilanja posjeda. Koncentracija zemljišta u rukama velikih globalnih kompanija izravno ugrožava produktivni kapacitet tla. Papa Franjo (2015) u enciklici *Laudato si'* formalizira tu povezanost stavom da je „sve povezano“. Ekološka kriza nije odvojiva od socijalne i ekonomske. Enciklika preuzima kategoriju subotnjeg odmora tla i jubileja kao model za promišljanje granica ekonomskog rasta (Franjo, 2015, br. 71; Pardon, 2016), a čovjekov poziv na obnovu odnosa prema tlu crpi iz biblijske teologije zemlje (Deane-Drummond, 2008).

Održivost najizravnije povezuje biblijsku teologiju tla s agroekologijom. Agroekosustav je cjelina koja uključuje tlo, bioraznolikost, klimu i socijalne odnose te zahtijeva periodičnu regeneraciju umjesto neprekidnog iscrpljivanja (Gliessman, 2015; Pretty, 2008). Ta je definicija analognu biblijskom subotnjem odmoru tla. On pretpostavlja da stalna eksploatacija uništava produktivnost te da je povremeno ograničenje uvjet dugoročne održivosti (Bašić, 2013b; Milgrom, 2001). Regenerativna poljoprivreda – kroz plodored, pokrovne usjeve i minimalnu obradu – prema biblijskim principima dobiva teološku legitimaciju kao praktična realizacija analognih normativnih načela (Thompson, 2017; Kisić i Posavec, 2025).

Biblijska agrarna etika i nove tehnologije: smjernice za razvoj suvremene agronomije

Suvremena se agronomija transformira pod utjecajem nove paradigmatičke nadgradnje. Za razliku od Industrije 4.0, koja je ciljala isključivo učinkovitost, Industrija 5.0 integrira antropocentrične vrijednosti i održivost u tehnološki razvoj (Dutta et al., 2025). U poljoprivredi se ta promjena očituje kroz preciznu poljoprivredu, autonomnu robotiku, senzorske mreže i algoritme umjetne inteligencije. Ti alati optimiziraju resurse na razini pojedinačne biljke (Dutta et al., 2026; Arora et al., 2026). Iako smanjuju ekološki otisak i jačaju prehrambenu sigurnost, ove tehnologije nisu etički neutralne. Ako se precizna poljoprivreda koristi samo za maksimizaciju prinosa, bez brige o pravednoj raspodjeli hrane, ona će produbiti društvene nejednakosti. Moć velikih agrobiznisa rast će na štetu malih proizvođača koji nemaju pristup skupim inovacijama. To je suvremena analogija starozavjetnoj proročkoj kritici gomilanja posjeda, gdje koncentracija tehnološke i podatkovne moći osigurava resurse nekolicini moćnih (Iz 5,8; Mih 2,1-2).

Zbog toga agronomija mora oblikovati etički okvir u kojem je tehnologija sredstvo za očuvanje plodnosti tla i pravednu raspodjelu hrane, a ne cilj sam po sebi. Papa Franjo u enciklici *Laudato si'* (br. 106-114) kritizira „tehnokratsku paradigmu“ i upozorava da rješavanje problema isključivo tehničkim sredstvima zanemaruje moralne dimenzije. U *Laudate Deum* dodatno naglašava da napredak bez regulacije produbljuje nejednakosti. Papa Lav XIV. u enciklici *Magnifica humanitas* proširuje ove stavove na digitalnu transformaciju, ističući da razvoj umjetne inteligencije mora služiti ljudskom dostojanstvu i zajedničkom dobru. Suvremena agronomija stoga mora premostiti teoriju i praksu; ona mora ponuditi znanstvene spoznaje, ali i čvrsto argumentirati potrebu za uvođenjem agroetičkih načela u podatkovne sustave poljoprivrede.



Biblijska etika upravljanja i čuvanja nudi jasne kriterije za tu provedbu. Pojmovi *abad* i *shamar* upućuju na to da svaku tehnološku intervenciju treba procjenjivati prema očuvanju regenerativnog kapaciteta tla i bioraznolikosti. Taj kriterij mora postati ograničavajući parametar u algoritmima precizne poljoprivrede (Deane-Drummond, 2019). Nadalje, princip subotnjeg odmora tla nudi ugrađivanje „granica intenzifikacije“ u automatizirane sustave odlučivanja. Algoritmi bi trebali imati mehanizme koji sprječavaju neprekidnu eksploataciju parcele, čak i kada je ona kratkoročno ekonomski isplativa (Altieri, 2018; Milgrom, 2001).

Tehnološki jaz između velikih i malih proizvođača i danas zahtijeva proročku kritiku (Clough, 2012). Biblijska zaštita siromašnih jasno pokazuje da se pristup tehnologijama i podacima ne smije prepustiti isključivo tržištu. Kao što je pabirčenje jamčilo pravo na hranu ranjivim skupinama, tako i moderna agronomija mora zahtijevati agrarne politike koje malim proizvođačima jamče pristup digitalnim alatima kroz javne investicije, otvorene podatke i subvencioniranu AI infrastrukturu (Finn, 2013; Zimdahl, 2012).

Teologija tla kao dara usmjerava agronome da regulaciju umjetne inteligencije ne prepuštaju samo tehničkim ekspertima i tržištu. U taj proces valja uključiti zemljoradničke zajednice, agronome i stručnjake za etiku. Institucionalna regulacija tehnologije mora počivati na jasnoj antropologiji koju biblijska agrarna etika nudi kao primjenjivu okosnicu za oblikovanje agrarnih politika u digitalnom dobu.

Zaključak

Etička pitanja u suvremenoj agronomiji više ne možemo svoditi samo na povećanje proizvodnje i tehnološki napredak. Klimatske promjene, degradacija tla, gubitak bioraznolikosti te primjena umjetne inteligencije jasno pokazuju da budućnost poljoprivrede podjednako ovisi o znanstvenim inovacijama i o vrijednosnim načelima. U tom kontekstu, biblijska teologija tla otkriva iznimno suvremen i primjenjiv normativni potencijal.

Analiza tekstova potvrđuje da Stari zavjet razvija dosljednu agrarnu etiku. U njoj je tlo Božji dar povjeren čovjeku na obrađivanje i čuvanje. Ustanove subotnje i jubilejske godine, proročka kritika gomilanja posjeda te zakoni o zaštiti siromašnih svjedoče o modelu koji čvrsto povezuje održivost, društvenu pravednost i odgovorno gospodarenje. Takvo se razumijevanje bitno razlikuje od čisto tržišnog vrednovanja tla te pruža jasne smjernice za modernu agrarnu etiku.

Iako ne nude moderne agronomske metode, biblijski tekstovi oblikuju etičke kriterije za vrednovanje proizvodnih sustava i tehnoloških inovacija. Digitalna poljoprivreda i umjetna inteligencija mogu pridonijeti održivosti jedino ako ostanu podređene zaštiti ljudskog dostojanstva, očuvanju tla i općem dobru.

Biblijska agrarna etika nije tek povijesna religijska baština, već koherentan sustav moralnih načela koji obogaćuje dijalog agronomije, ekologije i teologije. Integracijom tih spoznaja oblikujemo agronomiju utemeljenu na znanstvenoj izvrsnosti i etičkoj odgovornosti. Ako suvremeni agronomi, uz poznavanje zakonitosti tla, zanemare ove biblijske etičke temelje, riskiraju da osakate neizmjereno bogatstvo vlastitog agronomskog poziva. Zadaća suvremene agronomije nije otkrivati samo materijalne datosti tla, nego pronicati u zakonitosti čijom primjenom se njeguje i obrađuje duša i održava život tla.

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Cultivating the soul: The ethical dimension of agronomy in light of biblical teaching

Summary

This article provides an interdisciplinary analysis of the normative potential of biblical land theology for shaping contemporary agrarian ethics. Integrating biblical sciences, ecotheology, and socio-economic ethics, the study posits that biblical texts offer a coherent ethical framework for modern agronomic challenges. By critically evaluating intensive industrial agriculture, its moral legitimacy is questioned, emphasizing sustainability and social justice. Hermeneutical analysis of texts from Genesis, Leviticus, and prophetic literature demonstrates that the biblical concept of "land rest" anticipates the agroecological principles of regenerative farming. Furthermore, jubilee legislation lays the groundwork for agrarian reform and food justice, while the prophetic critique of land accumulation directly addresses structural issues within modern agribusiness. In conclusion, this research proves that biblical agrarian ethics provides an enduring value system and clear guidelines for sustainable cultivation, offering a vital ethical framework for responsible land stewardship amid global climate crises.

Keywords: biblical agrarian ethics; biblical land theology; ecotheology; sustainable agronomy



Nitrogen and magnesium content of apples available on the Zagreb market

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Abstract

Apple (*Malus × domestica* Borkh.) accounts for 22% of the fruit-growing area in Croatia. As a food, apples are recommended as part of a healthy daily diet due to their high nutritional value. The importance of this study lies in providing consumers with information on the sales channels where apples with the highest mineral content can be found. The aim of this study was to determine the nitrogen and magnesium content of apples available on the Zagreb market. Apple fruit samples were collected in triplicate on October 23, 2023, in the city of Zagreb from three markets, three retail chains, and three organic products stores. The results showed that the highest nitrogen content in dry weight (0.42% N) was found in apples purchased from retail chains, while the magnesium content was 0.03% Mg dry weight across all sales channels. When expressed on a fresh weight basis, the highest nitrogen content (69.12 mg N/100 g) was found in apples from markets, whereas the highest magnesium content (5.77 mg Mg/100 g) was recorded in apples from organic products stores. These findings indicate differences in nitrogen and magnesium concentrations among sales channels and provide useful information for consumers when selecting apples based on their nutritional and mineral composition.

Key words: fruit, macroelements, *Malus × domestica* Borkh., minerals, nutritional value

Introduction

Apple (*Malus × domestica* Borkh.) is one of the most widely cultivated and economically important fruit species worldwide. Apple fruits are valued for their nutritional composition and contain various nutrients and bioactive compounds, whose concentrations may vary depending on cultivar, origin, and production conditions (Kalinowska et al., 2014; Skinner et al., 2018).

Nitrogen (N) is an essential plant nutrient with an important role in plant growth and development, as well as in fruit yield and quality. It is a structural component of amino acids, proteins, nucleic acids, chlorophyll, and numerous other compounds involved in plant metabolism (Vukadinović and Lončarević, 1997; Miljković, 2021). Both N deficiency and excessive N supply can negatively affect apple growth, fruit development, yield, and quality (Vukadinović and Vukadinović, 2011; Miljković, 2021).

Magnesium (Mg) is also an essential plant nutrient and plays a central role in photosynthesis as a constituent of chlorophyll. In apple, Mg is involved in sugar formation and numerous enzymatic processes and contributes to energy metabolism (Vukadinović and Vukadinović, 2011; Miljković, 2021). Its availability and content in plants are influenced by soil properties, climatic conditions, nutrient interactions, and crop management (Mikkelsen, 2010).

The aim of this study was to determine the N and Mg content of apple fruits and to compare it according to the place of purchase and the presumed production system.



Material and Methods

For analyzing nitrogen (N) and magnesium (Mg) content, apple fruit sampling was carried out on 23 October 2023 in the city of Zagreb, Croatia. Apples were collected from three different sales channels, with three different sales points within each channel:

- a) 3 markets: Savica (TRŽ 1), Kvatrić (TRŽ 2), and Dolac (TRŽ 3)
- b) 3 retail chains: Konzum (TL 1), Eurospin (TL 2), and Plodine (TL 3)
- c) 3 organic products stores: bio&bio (TEP 1), Spar Natur Plus (TEP 2), and Priroda i Društvo (TEP 3).

Each sample was collected in triplicate to ensure result reliability. Additional information on apple production practices was obtained by reviewing product labels and through conversations with vendors. At Savica market, information indicated that the apples were organically produced. At Kvatrić market, the apples were assumed to have been conventionally produced using mineral fertilizers. At Dolac market, it was confirmed that the orchard from which the purchased apples originated was 10 years old and that the apple trees had undergone winter spraying. In all 3 retail chains, the apple samples were not labeled as organic products; therefore, they were assumed to have been conventionally produced, i.e., using mineral fertilizers. In contrast, apple samples collected from stores specializing in organic products – were organically produced, as these stores primarily sell products originating from certified organic production and bearing the corresponding organic label.

Chemical analysis of the composite apple samples was conducted at the Analytical Laboratory of the Department of Plant Nutrition, Faculty of Agriculture, University of Zagreb. The apple fruits were chopped and dried at 105 °C, after which they were ground and homogenized. Nitrogen was determined using the modified Kjeldahl method (HRN ISO 11261:2004), while Mg was determined by atomic absorption spectrometry following digestion with concentrated HNO₃ and HClO₄ in a microwave digestion system (AOAC, 2015).

Statistical analysis of the data was performed using analysis of variance (ANOVA) in SAS. SAS System for Windows, version 9.1 (SAS Institute Inc.), was used, and differences among means were tested using Tukey's test for significant differences (SAS, 2002–2003).

Results and Discussion

The average dry matter content of apple fruits differed significantly among sales channels (Table 1). The highest dry matter content was measured in samples from organic product stores (21.63%), while lower values were found in markets (17.11%) and retail chains (16.52%). Among individual sales points, the highest dry matter content was recorded in TEP 2 (25.26%), whereas the lowest values were observed in TL 1 (15.52%), TRŽ 1 (15.69%), and TL 3 (15.79%).



Table 1. Dry matter (% DM) content determined in apple samples collected from markets, retail chains and organic product stores

Sales channels		% dry matter			
Markets (TRŽ)	TRŽ 1	15.69	e	17.11	b
	TRŽ 2	17.31	d		
	TRŽ 3	18.34	cd		
Retail chains (TL)	TL 1	15.52	e	16.52	b
	TL 2	18.24	c		
	TL 3	15.79	e		
Organic product stores (TEP)	TEP 1	18.40	c	21.63	a
	TEP 2	25.26	a		
	TEP 3	21.22	b		

*Different letters represent significantly different values according to Tukey's test ($p < 0.05$). Values followed by the same letter are not significantly different.

The nitrogen (N) content in dry matter differed significantly among sales channels (Table 2). The highest average value was found in samples from retail chains (0.42% N), followed by markets (0.40% N), with no significant difference between these two channels. A significantly lower N content was determined in samples from organic product stores (0.29% N). Among individual sales points, the highest nitrogen content was found in TL 1 (0.49% N), while the lowest was recorded in TEP 2 (0.25% N).

Table 2. Nitrogen content in dry matter of apple fruits determined in samples collected from markets, retail chains and organic product stores

Sales channels		% N in dry matter			
Markets (TRŽ)	TRŽ 1	0.47	ab	0.40	a
	TRŽ 2	0.35	d		
	TRŽ 3	0.39	cd		
Retail chains (TL)	TL 1	0.49	a	0.42	a
	TL 2	0.33	de		
	TL 3	0.45	b		
Organic product stores (TEP)	TEP 1	0.32	e	0.29	b
	TEP 2	0.25	f		
	TEP 3	0.30	e		

*Different letters represent significantly different values according to Tukey's test ($p < 0.05$). Values followed by the same letter are not significantly different.

The N content expressed on a fresh matter basis showed a similar pattern (Table 3). The highest average values were found in samples from markets (69.12 mg N/100 g in fresh matter) and retail chains (69.07 mg N/100 g in fresh matter), with no significant difference between them. Samples from organic product stores had a significantly lower average N content (61.17 mg N/100 g in fresh matter). The highest individual value was recorded in TL 1 (76.58 mg N/100 g in fresh matter), while the lowest was found in TEP 1 (58.27 mg N/100 g in fresh matter).



Table 3. Nitrogen content in fresh matter of apple fruits determined in samples collected from markets, retail chains and organic product stores

Sales channels		mg N/100 g in fresh matter			
Markets (TRŽ)	TRŽ 1	74.29	ab	69.12	a
	TRŽ 2	61.07	c		
	TRŽ 3	72.01	ab		
Retail chains (TL)	TL 1	76.58	a	69.07	a
	TL 2	60.19	c		
	TL 3	70.45	b		
Organic product stores (TEP)	TEP 1	58.27	c	61.17	b
	TEP 2	62.32	c		
	TEP 3	62.93	c		

*Different letters represent significantly different values according to Tukey's test ($p < 0.05$). Values followed by the same letter are not significantly different.

The average magnesium (Mg) content in dry matter ranged from 0.027 to 0.030% Mg (Table 4), with no significant differences among sales channels. At individual sales points, the highest Mg content was recorded in TL 1 (0.03 %Mg), while the lowest values were found in TRŽ 2 (0.02% Mg) and TL 2 (0.02%Mg).

Table 4. Magnesium content in dry matter of apple fruits determined in samples collected from markets, retail chains and organic product stores

Sales channels		% Mg in dry matter			
Markets (TRŽ)	TRŽ 1	0.03	bc	0.027	a
	TRŽ 2	0.02	d		
	TRŽ 3	0.03	bc		
Retail chains (TL)	TL 1	0.03	a	0.027	a
	TL 2	0.02	cc		
	TL 3	0.03	bc		
Organic product stores (TEP)	TEP 1	0.03	bc	0.030	a
	TEP 2	0.03	b		
	TEP 3	0.03	bc		

*Different letters represent significantly different values according to Tukey's test ($p < 0.05$). Values followed by the same letter are not significantly different.

In fresh matter, the highest average Mg content was found in samples from organic product stores (5.77 mg Mg/100 g in fresh matter), which was significantly higher than in markets (4.24 mg Mg/100 g in fresh matter) and retail chains (4.40 mg Mg/100 g in fresh matter) (Table 5). Among individual sales points, the highest Mg content was recorded in TEP 2 (6.90 mg Mg/100 g in fresh matter), while the lowest was observed in TRŽ 2 (3.69 mg Mg/100 g in fresh matter).



Table 5. Magnesium content in fresh matter of apple fruits determined in samples collected from markets, retail chains and organic product stores

Sales channels		mg Mg/100 g in fresh matter			
Markets (TRŽ)	TRŽ 1	4.13	ef	4.24	b
	TRŽ 2	3.69	g		
	TRŽ 3	4.89	c		
Retail chains (TL)	TL 1	4.66	cd	4.40	b
	TL 2	4.50	de		
	TL 3	4.05	fg		
Organic product stores (TEP)	TEP 1	4.97	c	5.77	a
	TEP 2	6.90	a		
	TEP 3	5.44	b		

*Different letters represent significantly different values according to Tukey's test ($p < 0.05$). Values followed by the same letter are not significantly different.

The dry matter content of apple fruits differed among sales channels, with the highest value found in samples from organic product stores (21.63%). These values were higher than those reported for 'Golden Delicious' apples by Nour et al. (2010) and Mitre et al. (2009), who found approximately 14.7% dry matter. Such differences may be associated with cultivar, fruit maturity, and storage conditions.

Nitrogen content also varied among sales channels, with higher values in apples from retail chains and markets than in those from organic product stores. Kowalczyk et al. (2017) reported that increasing N fertilization increased N content in apple fruits, indicating that fertilization practices may contribute to differences in fruit N content. However, other factors, including cultivar, environmental conditions, harvest time, and storage, may also influence fruit nutrient composition. Magnesium content in dry matter did not differ significantly among sales channels, whereas on a fresh matter basis, the highest value was found in apples from organic product stores (5.77 mg Mg/100 g). Nour et al. (2010) reported 5.16 mg Mg/100 g fresh matter in 'Golden Delicious', which is comparable to the values obtained in the present study. Stanisavljević et al. (2008) also showed that apple fruit mineral composition can be affected by environmental and production factors.

Overall, the observed variability in N and Mg content cannot be attributed only to the sales channel, as differences in production practices, cultivar, environmental conditions, and postharvest handling may also contribute to fruit mineral composition.

Conclusion

The results demonstrated significant differences in the nitrogen (N) and magnesium (Mg) content of apple fruits among sales channels. Apples from retail chains and markets had the highest N content, whereas apples from organic product stores had the highest dry matter content and significantly higher Mg content in fresh matter. In contrast, Mg content in dry matter did not differ significantly among sales channels. Overall, the results indicate that the composition of commercially available apples varies among sales channels and that these differences depend on the nutrient and whether its content is expressed on a dry or fresh matter basis. These findings provide additional information on the nutritional composition of apples available through different sales channels and may be useful to consumers when selecting apples.



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Spatial variability of heavy metals and associated ecological and human health risks at the Kolubara a coal-fired thermal power plant complex

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Abstract

Coal-fired thermal power plants may cause long-term soil contamination through emissions, coal handling, and coal combustion residues. This study assessed the spatial and interannual variability of Pb, Cd, Hg, As, Cr, Cu, Ni, and Zn in soil and the associated ecological and human health risks at 17 locations within and around the Kolubara A Thermal Power Plant Complex during 2023–2024. Heavy metal concentrations showed pronounced spatial heterogeneity. Pb, Cr, and Zn increased significantly in 2024, whereas Hg concentration and the Potential Ecological Risk Index (RI) decreased. RI ranged from 228.14–978.34 in 2023 and 182.84–253.18 in 2024, although the decrease should be interpreted cautiously because Hg values in 2024 were set at the limit of quantification. The Hazard Index remained below 1, while Total Risk exceeded $1 \cdot 10^{-6}$ at all locations and was dominated by inorganic As. The results support continued site-specific monitoring and targeted management of the most affected locations.

Keywords: Coal Combustion Residues, Ecological Risk, Heavy metals, Human health risk, Soil contamination, Spatial variability

Introduction

Coal-fired thermal power plants may cause long-term soil contamination through atmospheric emissions, coal handling, and the disposal and redistribution of coal combustion residues (Kirsch, 2020; Finkelman et al., 2021; Hendryx et al., 2020). These processes can produce pronounced spatial variability in potentially toxic metal concentrations within and around industrial complexes (Oberschelp et al., 2019; Ćujić et al., 2016). However, studies integrating metal concentrations with ecological and human health risk assessments remain comparatively limited (Dong et al., 2024; Lin et al., 2023; Kravchenko et al., 2025; Sanad et al., 2025). The Kolubara A Thermal Power Plant Complex, characterized by a long operational history and an extensive ash and slag disposal area, provides a relevant setting for such an assessment. Therefore, this study evaluated the spatial and interannual variability of heavy metal concentrations within and around the KTPPC during 2023–2024 and assessed the associated ecological and human health risks.

Material and Methods

Study area

KTPPC is located in Veliki Crljeni, central Serbia. Constructed in 1956, the complex covers approximately 180 ha, including 100 ha occupied by the ash and slag disposal site. It is situated near the Kolubara, Turija, Seona, and Beljanica rivers, within an area characterized by a dense



network of permanent and intermittent watercourses. The area is characterized by a temperate continental climate, with pronounced seasonal variability in temperature, rainfall, and wind, and a mean annual rainfall of 763.9 mm for 1991–2022 period (RHSS, 2026). The geological framework of the area consists of Quaternary alluvial sediments (Haplic Fluvisol (Clayic) IUSS Working Group WRB, 2015) (Filipović et al., 1975; Tanasijević et al., 1963). The wider KTPPC area is characterized by a dense network of watercourses as well as a mosaic of urbanized, agricultural, and natural areas.

Monitoring design, soil sampling and laboratory analyses

Soil monitoring within the KTPPC was conducted in 2023 and 2024 by accredited laboratories commissioned by Elektroprivreda Srbije (EPS), and the resulting monitoring data were used in this study. Soil samples were collected from 17 predefined locations representing four functional sectors: electrical infrastructure (Z1–Z2), storage and operational facilities (Z3–Z5, Z7, and Z9–Z11), coal and ash management areas (Z6, Z8, and Z12–Z13), and peripheral comparison sites (Z14–Z17) (Figures 1a and 1b). At each location, 5 subsamples were collected from the 0–30 cm surface to form a composite sample. Total concentrations of Pb, Cd, Hg, As, Cr, Cu, Ni, and Zn were determined. Soil samples were extracted according to SRPS ISO 11466:2004, and Cd, Cr, Cu, Pb, Ni, Zn, and As were quantified by AAS according to SRPS ISO 11047:2004, while Hg was determined by MP-AES following EPA 3051 digestion.

Potential ecological risk assessment of heavy metals

The potential ecological risk RI associated with the analysed elements was assessed using the method proposed by Hakanson (1980). The contamination factor (Cf_i), individual potential ecological risk index (Er_i), and overall potential ecological risk index (RI) were calculated as follows:

$$Cf_i = C_i / C_{ref_i} \quad Er_i = Tr_i \cdot Cf_i \quad RI = \sum Er_i$$

where C_i is the measured total concentration of element i , C_{ref_i} is its reference concentration, and Tr_i is the corresponding toxic-response factors of 40 for Hg, 30 for Cd, 10 for As, 5 for Pb, Cu, and Ni, 2 for Cr, and 1 for Zn (Hakanson, 1980). Reference concentrations were adopted from national geochemical data and relevant literature (Ministry of Environmental Protection of the Republic of Serbia, 2010; Zhang et al., 2016). The RI was calculated separately for each sampling location and monitoring year using the total concentrations of Cd, Hg, As, Pb, Cu, Ni, Cr, and Zn and classified as low ($RI < 150$), moderate ($150 \leq RI < 300$), considerable ($300 \leq RI < 600$), or very high ($RI \geq 600$) ecological risk (Håkanson, 1980; Hu et al., 2013).

Human health risk assessment

Human health risks associated with soil contamination were assessed using the RAIS (Risk Assessment Information System) site-specific risk calculator (Oak Ridge National Laboratory, 2024). The assessment was performed using the Outdoor Worker exposure scenario, site-specific contaminant concentrations, and locally relevant exposure parameters. Non-carcinogenic risk was expressed as the Hazard Index (HI), while carcinogenic risk was expressed as Total Risk. Both indices were calculated by considering ingestion, dermal contact, and inhalation exposure pathways. HI values below 1 were considered to indicate no significant non-carcinogenic risk, whereas carcinogenic risk values were interpreted relative to the target risk benchmark of $1 \cdot 10^{-6}$. Interannual differences between 2023 and 2024 were assessed with the 17 monitoring and spatial distribution of RI was visualized using inverse distance weighting (IDW) interpolation.



Statistical Analyses

Interannual differences among the same 17 locations were assessed using repeated-measures ANOVA or the Friedman test, as appropriate. Statistical significance was set at $p < 0.05$.

Results and Discussion

Heavy metal concentrations showed pronounced spatial heterogeneity across the 17 monitoring locations (Table 1). The greatest variability was observed for Pb, Cu, Zn, and As, whose high coefficients of variation indicated localized concentration hotspots rather than uniform contamination across the study area. For several elements, particularly Pb, Cu, and Zn, mean concentrations exceeded the corresponding medians, further suggesting that elevated values were concentrated at a limited number of locations. Paired comparison showed significant interannual increases in Pb, Cr, and Zn, with mean concentrations rising from 53.31, 76.29, and 97.34 mg kg⁻¹ in 2023 to 58.77, 85.02, and 102.64 mg kg⁻¹ in 2024, respectively. Hg decreased significantly, whereas no significant interannual differences were observed for Cd, As, Cu, or Ni. Cd remained at LOQ in both years, while all Hg results in 2024 were reported at the LOQ; consequently, their limited variability partly reflects analytical censoring, and the apparent temporal pattern of Hg should be interpreted cautiously. Overall, spatial heterogeneity was more pronounced than uniform interannual change.

Table 1. Descriptive statistics of heavy metal concentrations, ecological risk index, and human health risk indices in 2023 and 2024, including the results of the paired Wilcoxon signed-rank test

Year	Parameter	Pb	Cd	Hg	As	Cr	Cu	Ni	Zn	RI	HI	Total Risk
2023	N	17	17	17	17	17	17	17	17	17	17	17
	Mean, mg kg ⁻¹	53.31	0.80	0.99	23.73	76.29	48.69	70.72	97.34	503.43	0.405	1.55E-04
	Median, mg kg ⁻¹	38.55	0.80	0.89	15.69	84.56	35.54	74.64	82.00	483.92	0.385	1.04E-04
	Standard deviation	44.67	0.00	0.41	14.84	37.56	38.36	28.06	63.17	158.67	0.148	9.51E-05
	Minimum, mg kg ⁻¹	8.93	0.80	0.25	3.98	23.93	7.90	22.90	25.36	228.14	0.190	2.66E-05
	Maximum, mg kg ⁻¹	170.41	0.80	2.24	60.56	150.96	150.64	137.41	260.18	978.34	0.785	3.92E-04
	Coeff. of variation (%)	83.80	0.00	41.85	62.54	49.23	78.79	39.68	64.90	31.52	36.69	61.20
2024	N	17	17	17	17	17	17	17	17	17	17	17
	Mean, mg kg ⁻¹	58.77	0.80	0.25	27.34	85.02	49.92	74.11	102.64	213.33	0.367	1.79E-04
	Median, mg kg ⁻¹	42.75	0.80	0.25	20.32	90.41	34.51	74.32	77.53	219.43	0.337	1.34E-04
	Standard deviation	42.36	0.00	0.00	13.50	33.68	37.15	27.19	62.91	20.45	0.129	8.64E-05
	Minimum, mg kg ⁻¹	29.17	0.80	0.25	12.55	31.26	18.35	41.67	54.12	182.84	0.212	8.34E-05
	Maximum, mg kg ⁻¹	177.13	0.80	0.25	53.23	153.49	147.23	145.18	270.12	253.18	0.611	3.45E-04
	Coeff. of variation (%)	72.07	0.00	0.00	49.38	39.61	74.43	36.69	61.29	9.59	35.02	48.29
Wilcoxon signed-rank		30.0*	—	0.0**	49.0	27.0*	57.0	61.0	25.0*	1.0**	35.0	44.0

Note: Heavy metal concentrations are expressed in mg kg⁻¹, whereas RI, HI, and Total Risk are dimensionless. For Cd and Hg results reported below the limit of quantification (LOQ), the corresponding LOQ values of 0.80 mg kg⁻¹ for Cd and 0.25 mg kg⁻¹ for Hg were used in the statistical and risk calculations. * $p < 0.05$; ** $p < 0.01$. The Wilcoxon statistic was not calculated for Cd because all paired values were identical.

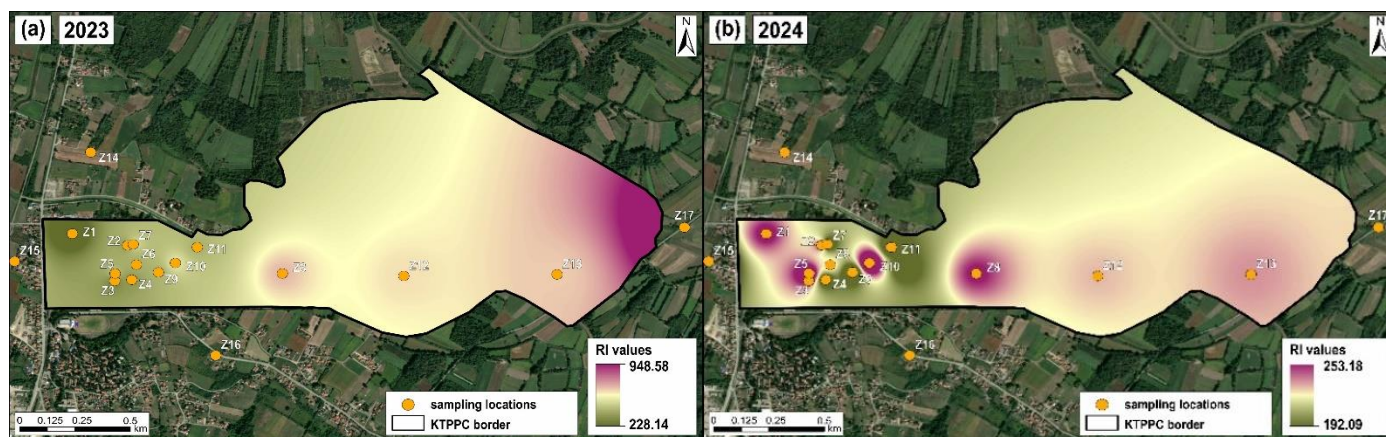


Figure 1. Interpolated spatial distribution of the ecological risk index (RI) within the KCTPPC boundary in (a) 2023 and (b) 2024

The ecological risk index showed marked spatial and interannual variability (Table 1; Figure 1). RI decreased significantly from 228.14–978.34 in 2023, with a mean of 503.43, to 182.84–253.18 in 2024, with a mean of 213.33. In 2023, one location had moderate, 13 considerable, and three very high ecological risk, whereas all locations had moderate risk in 2024. The highest RI occurred at peripheral site Z17 in 2023 and at operational site Z10 in 2024, indicating that elevated risk was not confined to a single functional sector. The decline was driven mainly by Hg, whose individual risk index ranged from 100 to 896 in 2023 but remained at 100 in 2024, while Cd contributed a constant value of 48 in both years. Because all Hg concentrations in 2024 were reported at the LOQ, the magnitude of the RI reduction should be interpreted cautiously.

The non-carcinogenic Hazard Index showed moderate spatial variability but no significant interannual difference. HI ranged from 0.190 to 0.785 in 2023 and from 0.212 to 0.611 in 2024, while the mean decreased from 0.405 to 0.367. HI remained below 1 at all locations, indicating that appreciable non-carcinogenic effects were not expected under the assessed Outdoor Worker scenario. Total Risk ranged from $2.66 \cdot 10^{-5}$ to $3.92 \cdot 10^{-4}$ in 2023 and from $8.34 \cdot 10^{-5}$ to $3.45 \cdot 10^{-4}$ in 2024. Although the mean increased from $1.55 \cdot 10^{-4}$ to $1.79 \cdot 10^{-4}$, the interannual difference was not significant. Total Risk exceeded the target benchmark of $1 \cdot 10^{-6}$ at all locations in both years. Inorganic As dominated both risk indices, contributing 54.73–69.58% of HI and approximately 98% of Total Risk. Cr(VI) was the main secondary contributor, while Hg contribution to HI decreased from 26.15% to 7.25% (Figure 2). This decline should be interpreted cautiously because all Hg concentrations in 2024 were reported at the LOQ.

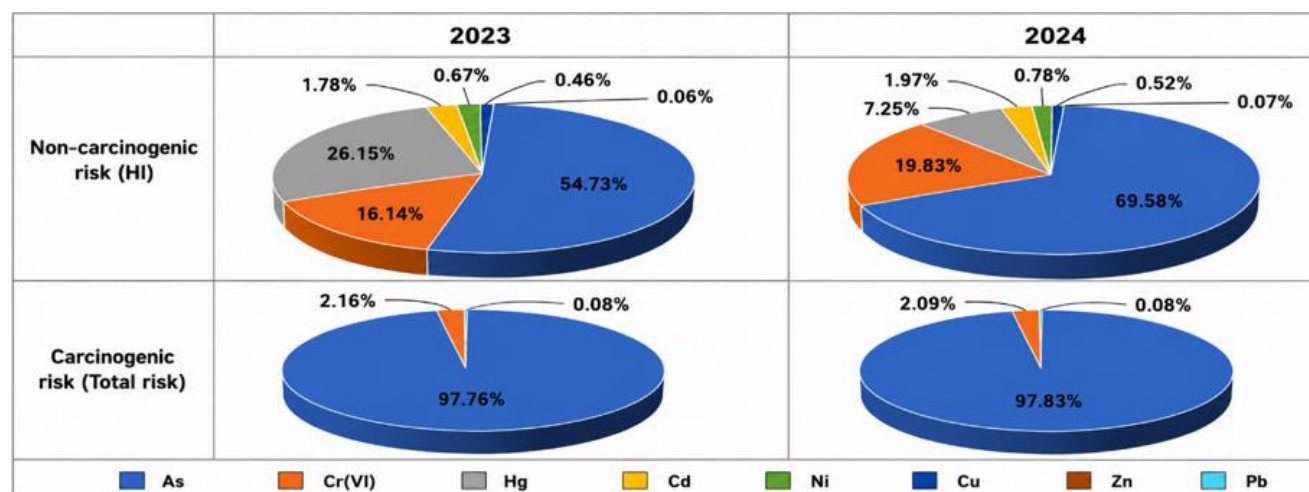


Figure 2. Relative contributions of individual contaminants to non-carcinogenic risk, expressed as the Hazard Index (HI), and carcinogenic risk, expressed as Total Risk, in 2023 and 2024

Conclusion

Soils within and around the KTPPC exhibited pronounced spatial heterogeneity, indicating localized rather than uniformly distributed heavy metal contamination. Significant interannual differences were observed for Pb, Cr, Zn, Hg, and RI, with Pb, Cr, and Zn increasing in 2024, while Hg and RI decreased. However, the marked reduction in RI should be interpreted cautiously because Hg concentrations in 2024 were reported at the limit of quantification and the corresponding LOQ value was used in the risk calculations. Non-carcinogenic risk remained below the threshold of concern at all locations, whereas carcinogenic risk exceeded the target benchmark of $1 \cdot 10^{-6}$ throughout the study area and was almost entirely dominated by inorganic As. The occurrence of elevated ecological and health-risk values both within operational sectors and at peripheral sites confirms that risk was not confined to the industrial core. Continued site-specific monitoring, improved analytical resolution for Hg and Cd, and targeted management of locations with persistently elevated metal concentrations and risk indices are therefore recommended.

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Doprinos društvu kroz znanost i tehnologiju

Shimadzu je vodeći svjetski proizvođač analitičkih i mjernih instrumenata. Nudimo sofisticirana i optimalna rješenja neophodna za istraživanje, razvoj i kontrolu kvalitete.

Naša rješenja!

Sustavi za plinsku kromatografiju (GC) osiguravaju pouzdanu i osjetljivu analizu hlapljivih spojeva sadržanih u uzorku.



Masena spektrometrija s induktivno spregnutom plazmom (ICP-MS) je tehnika u kojoj se induktivno spregnuta plazma koristi kao ionizacijski izvor, a detekcija se vrši masenom spektrometrijom.



Spektrofotometri mjere intenzitet svjetlosti koju apsorbiraju ili emitiraju kemijske tvari.



Analizatori ukupnog organskog ugljika (TOC) mjere ukupnu količinu organskog ugljika u vodi, plinovima i čvrstim tvarima. Zadovoljavaju raznolik raspon potreba u područjima kao što su istraživanje okoliša, kontrola kvalitete i upravljanje procesima.



Sustavi za tekućinsku kromatografiju (LC) uspješno razdvajaju tvari na osnovi razmjesta između čvrste stacionarne faze i tekuće mobilne faze.



Sustavi za plinsku kromatografiju - masenu spektrometriju (GC/MS) omogućuju brzu identifikaciju nepoznatih komponenti i preciznu kvantitativnu analizu, čak i za komponente u tragovima.



Sustavi za visoko učinkovitu tekućinsku kromatografiju (HPLC) podržavaju širok raspon aplikacija, uključujući analizu hrane, lijekova te uzoraka iz okoliša.



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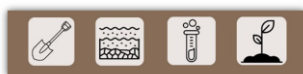
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