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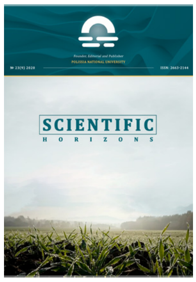

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Ecological aspects in the use of soil enzymes as indicators of anthropogenic soil pollution

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Abstract. In the contemporary era, with rapid industrial growth and urbanisation, analysing the impact of human activities on soil enzyme activity becomes crucial. The purpose of this study is to assess the influence of anthropogenic pollution on enzyme activity in soil. Research on enzyme activity levels in the soil in the city of Kara-Balta, Chuy Region, Kyrgyz Republic, was conducted using biochemical analyses and specific enzymatic tests. The results revealed significant diversity in catalase activity in

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different soil samples. Some samples exhibited high activity, while others showed low activity. These differences may be associated with oxidative stress and the ability of soil microorganisms to decompose hydrogen peroxide. Urease analysis indicated the highest activity in soil samples after 2 hours, particularly near the protective barrier of the tailings pond, suggesting intensive chemical reactions, especially near pollution sources. Research has also revealed the diversity of protease activity in soil ecosystems, where samples with high activity may more effectively break down proteins compared to samples with low activity. To achieve ecological stability of soil resources, it is necessary to develop a management strategy, including monitoring and restoring priority areas considering local characteristics, supporting biodiversity, applying sustainable agricultural methods, and combating soil erosion. Important steps also include forming a community emphasising the importance of soil resources, funding research, and collaborating with local authorities, scientists, and the business community. The results of the study can be used in developing strategies to prevent the negative consequences of soil pollution, contributing to improved ecological resilience, especially for environmental protection agencies

Keywords: catalase; urease; protease; ecosystem; ecological stability; sustainable development

INTRODUCTION

Soil is an integral part of biogeocenoses and the biosphere as a whole, performing important environmental functions. It sustains life on Earth, participates in the cycling of substances and energy in the biosphere, and contributes to ecosystem stability. However, under increasing anthropogenic pressure on the planet, soil undergoes degradation due to human activities. This affects all components of the biosphere and underscores the importance of assessing the state of the soil and its potential rehabilitation (Bartkowiak *et al.*, 2020).

Enzymes in the soil play a key role in biochemical processes, determining its functionality. They act as biocatalysts, facilitating the decomposition of organic matter and the circulation of biogenic elements in the soil. These enzymes can be produced by various organisms, as their activity creates complex biochemical systems in the soil (Doolotkeldieva *et al.*, 2021). The analysis of enzymatic activity in the soil is a powerful tool for assessing anthropogenic impact. It reflects the dynamics of essential biochemical processes, such as the decomposition of organic material and nitrification. These processes are crucial for maintaining soil health and the overall ecosystem (Totubaeva *et al.*, 2019).

Research on enzymatic activity allows evaluating the degree of ecosystem degradation and developing soil rehabilitation strategies. They can also help establish a quantitative relationship between the physicochemical properties of the soil and enzyme activity, contributing to a deeper understanding of changes occurring in the soil due to anthropogenic influence. Soil enzymes are a powerful tool for diagnosing contaminated soils and ecosystems. They reflect changes in the soil under the influence of pollutants such as oil, metals, and pesticides. Studies show that enzymes are sensitive indicators of pollution, and their activity may change depending on the type of pollutant and its concentration (Cui *et al.*, 2021).

In particular, enzymes such as urease, catalase, and dehydrogenase can be used to detect oil-contaminated soils. Urease often increases its activity in the presence of oil, associated with the growth of ammonifying microorganisms. However, after the completion of oil degradation processes, urease activity decreases, and catalase activity increases. These changes in enzyme activity can serve as indicators for diagnosing the state of the soil after oil contamination (Doolotkeldieva *et al.*, 2018). The use of soil enzymes as indicators of anthropogenic soil pollution in industrial cities of the Kyrgyz Republic is of great importance for assessing the environmental situation and soil health in the country. Like many other countries, the Kyrgyz Republic faces soil pollution issues in industrial regions, where intensive industrial activities can lead to emissions of various pollutants. This is particularly crucial for industrial cities, where the intensive use of soil and emissions from industrial enterprises can have a negative impact on soil quality (Severinenko *et al.*, 2023).

In this regard, researching enzyme activity in polluted soils provides an opportunity to diagnose and assess the degree of soil contamination by various pollutants such as oil, metals, or pesticides. Soil enzymes are sensitive to changes in the environment and can serve as indicators to detect the presence and nature of pollution. This enables taking measures to control and manage contaminated areas and developing strategies for their rehabilitation. Research on enzyme activity in polluted soils is also important in the context of climate change and the development of rehabilitation strategies for pollution. In addition, enzyme activity is linked to soil quality and its impact on human health through food products, making it relevant from a public health perspective. Thus, studies on enzyme activity have practical significance for addressing environmental, economic, and health issues in the modern world.

The purpose of this study is to assess how anthropogenic pollution affects enzyme activity in the soils of the industrial city of Kara-Balta. To achieve this purpose, the following tasks were set and implemented: evaluate the level of enzymatic activity in the soil in Kara-Balta, and develop recommendations for the management and monitoring of soil resources to preserve and restore environmental sustainability.

MATERIALS AND METHODS

The object of the study was the city of Kara-Balta, located in the Chui region, serving as the centre of the Jayyl district of the Kyrgyz Republic. The city is situated in the Chui Valley along the Kara-Balta River and is positioned on the route of the road connecting Bishkek, Taraz (Kazakhstan), and Tashkent (Uzbekistan). Located at an altitude of 780 m above sea level, the city is 62 km west of the capital Bishkek and 122 km from the regional centre of Tokmok. Various sampling points were selected in different parts of the city for soil sample collection (Table 1).

***Table 1.** Points of selection of soil samples*

No.	Soil sampling points in the city of Kara-Balta	Coordinates of points
1	300 m from Djunda, in an agricultural area	42°47'42"N 73°50'34"E
2	100 m from the security zone	42°47'56"N 73°52'58"E
3	10 m from the security zone	42°47'56"N 73°53'00"E
4	200 m from the tailings tank	42°47'004"N 73°50'20"E
5	100 m from the tailings tank	42°47'15"N 73°50'11"E
6	50 m from the tailings tank	42°47'13"N 73°50'07"E
7	At the border of the protective barrier of the tailings pond	42°47'14"N 73°50'06"E
8	Inside the tailings pond	42°47'15"N 73°50'08"E
9	200m from Kara-Balta Mining and Metallurgical Plant (KMMP)	42°46'28"N 73°50'01"E
10	KMMP from a distance of 100m	42°46'28"N 73°50'01"E
11	Acreage 150m from KMMP	42°46'14"N 73°50'18"E
12	400m from KMMP	42°46'26"N 73°50'47"E
13	Control sample 1 km from KMMP	42°46'23"N 73°51'14"E

***Source:** compiled by the authors*

Samples were taken at a depth of 0-20 cm from a test area measuring 1×1 m at 5 different points, which were then combined into a single composite sample weighing 400-500 g. The following methodologies were employed to determine soil indicators:

1. Soil pH was determined using a universal ionomer EV-74.
2. Humus content in the soil was determined using a modified Tyurin method.
3. Soil moisture was determined by the gravimetric method, where samples were dried in an oven at a temperature of 105°C.
4. Soil particle size distribution was determined using the sieve method, using sieves of various sizes ranging from 0.001 to 10 mm.

For catalase activity determination, a method based on the formation of a complex of intact hydrogen peroxide with potassium iodide was used. Catalase activity was calculated using the formula: $A=D/0.02$, where A represents the catalase activity in the sample; D – optical density of the investigated sample; 0.02 – the conversion coefficient of catalase into arbitrary units.

For urease activity determination, an express method was employed. This involved placing 50 g of soil sample in a Petri dish and adding 0.5 g of urea dissolved in a small amount of water. The soil and urea were thoroughly mixed, moistened with distilled water to a paste-like state, and evenly distributed on the bottom of the dish. The dish was covered, and the incubation time was determined based on soil biological activity (2-3 hours, up to 4 hours in cold weather).

For protease activity determination, a modified photometric method was used, conducted in the laboratory of the fertility of hydromorphic and acidic soils of the Institute of Soil Science and Agrochemistry named after O.N. Sokolov. This method is based on the Mishustin method for determining protease activity, utilising photographic film, and an improved method for calculating protease activity using Adobe Photoshop.

The obtained research results were processed for reliability using a multifactor analysis of variance (ANOVA) with the help of Microsoft Excel and the Statistica 10 software package. Differences in the obtained results were considered significant at a significance level of $P \leqslant 0.05$ according to the Student's t-test criterion.

RESULTS

The city of Kara-Balta is characterised by the presence of several large industrial enterprises and has a tailings storage facility. The Zhongda Oil Refinery, located in Kara-Balta, was built in 2009 and started production in 2014. The owner of the refinery is the Chinese company China Petrol Company Zhongda LLC, and Kyrgyzstan does not have a share in its ownership. The refinery specialises in the production of various oil products, including gasoline, diesel fuel, mazut, and liquefied gas. About 89% of the produced products are sold on the domestic market, while the remaining 11%

are exported to countries such as China, Tajikistan, Belarus, and Uzbekistan. The refinery's operations have been suspended since October 2020.

The tailings storage of the Kara-Balta Mining Combine is located in the Jayyl district of the Chui region. This site has been used for storing radioactive waste since 1955 and is located only 1.5 km from the city of Kara-Balta, which has a population of over 50 thousand. Since 2008, the complex has belonged to the private enterprise "Uran-Platina Holding." The total volume of radioactive waste here is about 37 million m^3, although the designed capacity of the storage is almost twice as large – 63.5 million m^3. Some sections of the waste storage are undergoing constant rehabilitation. However, due to the complex economic situation at the Kara-Balta Mining and Metallurgical Plant (KMMP), the quality of supervision over the storage has deteriorated, posing an increased risk to the environment and the population in densely populated areas. The waste storage in Kara-Balta is considered one of the most dangerous objects in the Kyrgyz Republic and is the largest landfill of its kind in the world. The potential contamination zone extends to a radius of 10 km from this facility.

Agrochemical indicators of soil samples are crucial for understanding its condition in a region with industrial load. The analysis of agrochemical soil characteristics helps not only in determining the physical and chemical properties of the soil but also in developing strategies to improve its quality and increase productivity. It is important to emphasise that agrochemical soil indicators have a significant impact on agriculture and the environmental condition of the studied region. According to the obtained data, soil samples have different levels of acidity (pH), but most of them are in the neutral or slightly alkaline range, which is often favourable for agriculture. The humus content varies from low values around 2% to higher values around 6.5%. Samples with higher humus content can provide better soil fertility. Cation exchange capacity also varies among samples, which can affect the soil's ability to retain nutrients (Table 2).

Table 2. *Agrochemical indicators of the studied soil samples*

No.	pH	Humus, %	Absorption capacity, mg equiv per 100 g of soil
1	7.2	1.98	13.4
2	7	2.96	14
3	7.55	3.22	16
4	7.7	3.22	18.4
5	7.85	2.5	14.6
6	7.55	3.28	17
7	7.6	3.38	18
8	7.8	3.22	18
9	7.2	5.04	22
10	7.3	3.9	18
11	7.95	3.38	17.2
12	7.2	6.55	23
13	6.9	2.65	16

Source: *compiled by the authors*

The analysis of the mechanical composition is an important stage of the study, as it allows determining the percentage of various particles in the soil by their size. These data are of significant importance for evaluating the soil's textural characteristics, its ability to retain moisture and nutrients, and determining its agrochemical properties. The mechanical composition of the soil, including the proportions of sand, silt, and clay, determines its textural characteristics. In the conducted study, various soil samples exhibit different mechanical compositions. The soil at 10 m from the protected zone has a high content of the fraction sized 1-0.25 mm (24.79%), while the soil at the boundary of the tailings storage protective barrier has a higher content of the fraction 0.25-0.05 mm (32.2%). The soil sample from the sowing area at 150 m from KMMP has a significant content of the fraction <0.01 mm (26.12%) (Table 3).

Table 3. *Mechanical composition of the studied soil samples*

No.	Fraction content, % (particle size mm)							Sum of particles <0.01
	>1	1-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	<0.001	
1		14.72	12.4	41.48	1.44	16.24	13.72	31.4
2		12.21	9.41	32.2	11.12	19.56	15.4	46.08
3		18.61	24.79	22.56	4.48	19.92	9.64	34.04
4		10.21	18.79	29.92	8.08	17.52	15.45	41.08

Table 3, Continued

No.	Fraction content, % (particle size mm)							Sum of particles <0.01
	>1	1-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	<0.001	
5		12.9	17.58	28.92	10.68	17.24	12.68	40.6
6		21.74	21.86	24.56	8.64	12.8	10.4	31.84
7		11.99	19.13	32.2	8.48	16.36	11.84	36.68
8		15.4	18.2	30.76	9.84	13.44	12.36	35.64
9		13.18	13.38	35.04	10	17.04	11.36	38.4
10		16.91	14.97	29.56	11.24	14.64	12.68	38.56
11		20.33	17.11	36.44	4.32	12.88	8.92	26.12
12		20.66	19.5	24.72	7.88	14.88	12.36	35.12
13		20.76	33.56	31.84	9.08	14.46	10.56	34.6

Source: *compiled by the authors*

The catalase activity is an important indicator that can help determine the impact of anthropogenic changes on the soil. Locations with increased catalase activity may have mechanisms to protect against oxidative stress, while in other locations, the soil may be less resistant to this stress. The study of the activity of catalase and other soil enzymes is crucial for monitoring soil conditions and detecting anthropogenic impacts. This data can assist in developing environmental protection strategies and maintaining ecosystem stability in industrial cities.

As a result of the study, it was found that catalase activity varies significantly among samples, covering a wide range of values from 15.9 to 86.6. This indicates the different ability of soil samples to decompose hydrogen peroxide. Soil samples from 200 m from the tail tank and inside the tailings storage exhibit the highest catalase activity values. This may indicate their high capability to decompose hydrogen peroxide, potentially linked to greater resistance to oxidative stress. Soil samples from 50 and 100 m from the tail tank have the lowest catalase activity values, suggesting limited capability to decompose hydrogen peroxide. This may indicate higher vulnerability to oxidative stress, possibly related to anthropogenic influences. Other samples have activity values between these extremes, indicating diversity in their ability to decompose hydrogen peroxide (Table 4).

Table 4. *Catalase activity*

No.	D	A
1	0.41	20.5
2	0.318	15.9
3	0.851	42.55
4	0.933	46.65
5	0.246	12.3
6	0.245	12.25
7	0.318	15.9
8	1.732	86.6
9	0.862	43.1
10	0.838	41.9
11	0.749	37.45
12	0.842	42.1
13	0.739	36.95

Note: *D is the optical density of the test sample; A is the catalase activity in the sample*
Source: *compiled by the authors*

Results of urease activity measurements in different samples over time (1 hour, 1.5 hours, and 2 hours) show that the enzyme's activity varies among samples and changes over time. Initial values range from 3.5 to 5, and final values after 2 hours range from 6.5 to 8. This suggests various chemical processes occurring in the solutions, which can be a crucial factor in examining chemical reactions and the time impact on environmental parameters.

Significant increases in soil samples from 200 m from the tail tank and the control sample 1 km from KMMP may indicate chemical processes affecting the acidity or alkalinity of the solutions. Changes in urease activity over time indicate that chemical processes in the soil develop and change over time. This dynamic may be related to various factors such as microorganisms, the presence of organic substances, and environmental conditions. Thus, soil samples at the boundary of the tailings storage protective barrier and in the control sample demonstrate the highest urease activity values after 2 hours, potentially linked to more intense chemical reactions (Fig. 1).

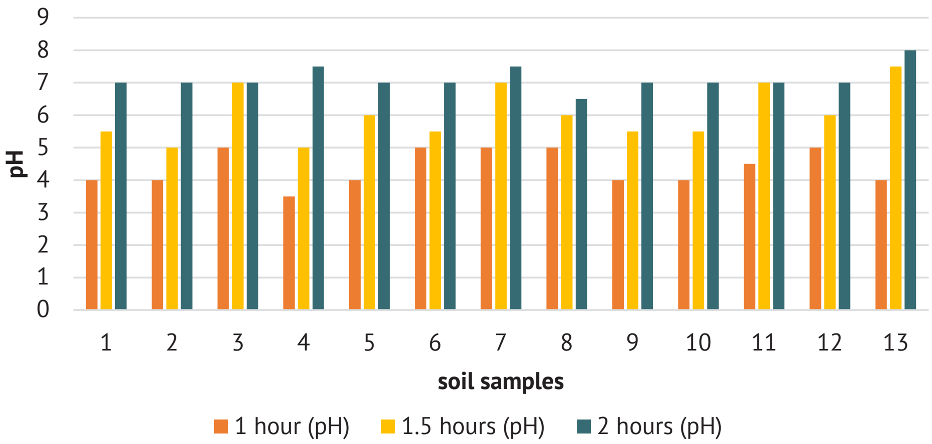

Figure 1. *Urease activity*

Source: *compiled by the authors*

Significant changes in soil samples, especially near pollution sources, may indicate the influence of anthropogenic chemical processes on soil acidity or alkalinity. This can have long-term effects on soil and biota and the quality of soil resources. The research results emphasise the importance of regular monitoring of soil enzymes, such as urease, in industrial city areas. This helps identify changes in the soil ecosystem and react promptly to anthropogenic impact. Information about changes in the soil ecosystem, occurring under the influence of anthropogenic factors, using the activity of protease enzymes as an indicator, was determined by the area of the decomposed gelatine layer – S(g). Values of S(g) vary significantly among the investigated samples. The minimum value is 0.267, while the maximum value is 7.318. This indicates diverse activity of protease enzymes in different soil samples.

Soil samples at 50 m from the tail tank and at the boundary of the tailings storage protective barrier stand out with the largest area of the decomposed gelatine layer. This may indicate higher activity of protease enzymes in these samples, possibly related to more intensive biochemical processes. Soil samples at 200 m from the tail tank and inside the tailings storage have the lowest S(g) values, indicating reduced activity of protease enzymes in these soils. This could be associated with the impact of anthropogenic factors that may slow down or restrict biochemical processes in the soil. Other samples have S(g) values between these extreme values, indicating diversity in the activity of protease enzymes in soils (Table 5).

Table 5. *Assessment of changes in the soil ecosystem under anthropogenic influence based on the activity of protease enzymes*

No.	S(g)
1	4.542
2	1.952
3	2.258
4	0.554
5	1.773
6	5.954
7	7.318
8	0.84
9	0.267
10	3.383
11	1.652
13	4.67

Note: *S(g) – area of the decomposed gelatine layer*
Source: *compiled by the authors*

Protease activity is directly related to the soil's ability to decompose organic material, including plant and animal residues. These processes play a crucial role in the nutrient cycle and soil stability. Therefore, changes in protease activity can affect soil quality and its ability to support plant and animal life. Analysing protease activity in different samples or conditions allows the following observations: the data demonstrate diversity in protease activity in samples, with minimum activity at 0.0002% and maximum reaching 0.04%. Such diversity indicates varying abilities of samples to decompose protein compounds. The soil sample at 300 m from the China Petrol Company Zhongda oil refinery, in the agricultural area, and the control sample 1 km from KMMP exhibit the highest protease activity. This may indicate a higher capacity for breaking down protein compounds in these samples, suggesting healthier soils in these locations.

Soil samples at 200 m from the tail tank, inside the tailings storage, and at 200 m from KMMP have the lowest protease activity. This indicates a reduced ability to decompose protein compounds in such samples, possibly due to pollutant impact and changes in soil conditions. The obtained data can be essential for understanding biochemical processes in the soil and other ecological systems and for assessing the soil's ability to decompose organic material (Table 6).

Table 6. *Protease activity, %*

1	0.03
2	0.01
3	0.02
4	0.0005
5	0.001
6	0.005
7	0.006
8	0.0007
9	0.0002
10	0.02
11	0.01
13	0.04

Source: *compiled by the authors*

In general, the study confirms that soil enzymes can serve as important indicators of anthropogenic impact on soils in industrial cities. This not only helps understand the environmental conditions but also enables measures to improve ecological sustainability in such areas. Recommendations for the management and monitoring of soil resources to preserve and restore ecological sustainability:

1. Develop a soil resource management strategy that includes goals and priorities for managing and restoring soil resources, considering local characteristics and environmental needs.

2. Monitor soil quality in vulnerable and ecologically important areas.

3. Preserve biodiversity by applying conservation and restoration methods, such as soil vegetation restoration and creating locations for animal migration.

4. Adopt sustainable agricultural practices, such as organic farming, and reduce the use of chemical fertilisers and pesticides.

5. Develop erosion stabilisation methods.

6. Educate and inform the public, agricultural workers, and all stakeholders about the importance of soil resource management and methods for preserving ecological sustainability.

7. Finance and support research aimed at studying soil processes, monitoring changes in soil ecosystems, and developing new methods for soil resource restoration.

8. Incorporate legislation and regulations that promote sustainable soil resource management, including penalties for soil damage and illegal construction on vulnerable soil sites.

9. Collaborate with local authorities, scientists, and the business community to develop and implement joint programmes for soil resource management and monitoring.

These recommendations form the basis for developing a comprehensive approach to soil resource management with the goal of preserving and restoring ecological sustainability. Effective soil management plays a crucial role in ensuring a healthy environment and sustainable development.

DISCUSSION

Soils are an essential component of ecosystems, supporting vegetation, filtering water, and participating in the nutrient cycle. However, industrial activities in cities often result in high levels of anthropogenic soil pollution. This pollution includes various chemical compounds such as heavy metals, organic compounds, petroleum products, and other harmful substances that can cause serious damage to soil ecosystems and human health.

According to Y. Cui *et al*. (2019), various methods and tools are employed to assess the degree of anthropogenic soil pollution in industrial cities. One of such methods is the use of soil enzymes as indicators. Soil enzymes are proteins that play a key role in the biochemical processes occurring in the soil. They can be sensitive to changes in the soil environment and serve as indicators of anthropogenic impact on the soil. The application of enzymes also contributes to the development of measures to restore soils affected by human activities, correlating with the conducted research and its findings. The study also reflects the opinion of S.H. Lee *et al*. (2020) that anthropogenic pollutants can affect the activity and structure of enzymes, which can be used to assess the pollution level. Metals such as copper, nickel, and mercury can inhibit the activity of various soil enzymes, depending on their concentration and the enzymes' properties. These metals can have diverse effects on soil biochemical processes.

Furthermore, the activity of soil enzymes can be influenced by pesticides, and this impact depends on their chemical structure and bioavailability. The chemical structure of pesticides can affect how they interact with soil enzymes. Some pesticides may inhibit or destroy the activity of specific enzymes, leading to disruptions in processes related to the decomposition of organic matter or nutrient cycling. This can lead to a deterioration in soil quality and a decrease in its fertility (Masikevych *et al*., 2022). According to C. Michan *et al*. (2021), substances entering the soil due to anthropogenic influence can alter enzymatic activity, serving as an indicator of pollution. Toxic trace elements and petroleum hydrocarbons can have a negative impact on the activity of soil enzymes, affecting the soil's ability to support life and ecosystem functions, as also noted in the conducted study.

Confirmation of the conducted research can also be found in the works of R. Nunes *et al*. (2021), who argue that soil enzymes can be used for conducting ecotoxicological studies to assess the impact of pollutants on biological systems in the soil. The use of soil enzymes also facilitates monitoring anthropogenic soil pollution in industrial areas, which can be useful for taking measures to improve soil quality and environmental protection, as also reflected in the conducted study. Moreover, studies on soil enzyme activity help assess the health of an entire ecosystem, and the functionality of the soil and its ability to support life in the ecosystem are linked to enzyme activity. Changes in enzyme activity may indicate alterations in biological diversity and the structure of soil microorganisms, which, in turn, influence ecosystem processes. Such research allows not only the evaluation of the current state of the biogeocenosis but also the prediction of its ability to recover after potential pollutant impacts. These studies help make informed decisions in environmental protection and strategy development to minimise pollutant impact on natural ecosystems, as reflected in the arguments presented in the current study (Maphuhla *et al*., 2020; Maini *et al*., 2020).

C.M. Raffa and F. Chiampo (2021) emphasise the importance of understanding how soil pollution levels, chemical and biological properties influence the synthesis, activity, and stability of enzymes, their release into the environment, and distribution in the soil under increasing human impact on soil ecosystems. This knowledge plays a key role not only in soil enzymology and microbiology ecology but also in determining the effectiveness of soil restoration methods affected by anthropogenic influences. R. Ochoa-Hueso *et al*. (2021) confirm the results of the study that soil-forming factors, such as soil composition, influence the nature and formation of enzymes. Soil represents a complex biological and physicochemical system, complicating the study of microbiological processes occurring in it. This highlights the need for collaboration among specialists from different fields to more accurately determine the impact of various factors on biochemical processes in different soil types and climatic conditions (Nazarkulova *et al*., 2019; Keller *et al*., 2021).

Advancements in the use of soil enzymes are crucial for environmental protection and natural resource management. Soil enzymes can catalyse the decomposition of pollutants, such as chemicals and heavy metals, into less toxic products. This can be highly valuable for soil restoration and the cleanup of contaminated areas. Soil enzymes can be used for real-time pollution level monitoring and assessing the effectiveness of methods for rehabilitating polluted soils. It also helps determine the necessary measures for restoring soil resources (Koković *et al*., 2021; Wyszkowska *et al*., 2023). Numerous studies by authors, particularly M.A. Severinenko *et al*. (2023), Y. Tepe *et al*. (2022), also emphasise the significant role of soil enzymes in processing tissues contaminated with various chemical substances. Soil enzymes exhibit high activity and the ability to catalyse specific reactions necessary for breaking down both natural and synthetic compounds into less hazardous substances. Soil enzymes also perform diverse functions, such as decomposing organic substances, mineralising nutrients, and detoxifying harmful compounds, as also demonstrated in the conducted studies.

According to the data from N. Totubaeva *et al*. (2019), the use of the soil enzyme urease as an indicator of anthropogenic soil pollution in industrial cities provides crucial information about the state of the environment and the impact of human activities on soil ecosystems. The study shows that urease activity varies among different soil samples. This variation may be related to different pollution factors, such as industrial emissions, the presence of toxic substances, and changes in soil conditions. The diverse dynamics of urease activity over time indicate that anthropogenic influence and chemical processes in the soil are not static but evolve over time. This can be linked to the continuous impact of pollutants and changes in environmental conditions, as confirmed in the study.

Considering the mentioned studies by the authors and the results of this study, it can be asserted that the use of soil enzymes as indicators of anthropogenic soil pollution in industrial cities is an essential tool for assessing the state of soil ecosystems and developing measures for their restoration. This approach not only helps identify issues related to soil pollution but also contributes to improving the resilience of urban ecosystems and ensuring a healthy environment for residents. Furthermore, it is crucial to continue research in this field and develop more precise methods for assessing the activity of soil enzymes and their relationship with anthropogenic impacts to more effectively address environmental issues associated with soil pollution.

CONCLUSIONS

The use of soil enzymes as indicators of anthropogenic pollution in industrial cities is of great significance for assessing the environmental condition and taking measures to improve the quality of the environment and human health. These indicators not only help identify pollution but also provide information for the development of sustainable development and environmental protection strategies.

The study disclosed that the examination of catalase activity shows significant diversity in the ability of different soil samples to decompose hydrogen peroxide. Some samples exhibit high activity, while others have low activity. This variation may be associated with differences in oxidative stress and the ability to biochemically break down hydrogen peroxide. Observations of the highest urease activity in soil samples after 2 hours, especially at the border of the tailings storage protective barrier, indicate more intensive chemical reactions, particularly in areas located in close proximity to the pollution source. This may be related to biotic and abiotic factors, including microorganisms and changes in soil composition. The analysis of protease activity in the soil ecosystem also shows diversity in the ability of different soil samples to decompose protein compounds. Samples with high protease activity may more effectively break down proteins, while samples with low activity may be less capable of doing so.

To achieve ecological sustainability of soil resources, it is important to develop a management strategy that includes monitoring and restoring priority areas, considering local characteristics. This involves ensuring high-quality monitoring of soil conditions, maintaining biodiversity, adopting sustainable agricultural methods, and combating soil erosion. Public education on the importance of soil resources and funding research play a crucial role in this process. In addition, legislative consideration and collaboration with local authorities, scientists, and the business community help ensure effective management and monitoring of soil resources, contributing to their sustainability and preservation for future generations. Further studies can focus on developing more efficient methods for monitoring soil enzymes, allowing for a more accurate and timely determination of the degree of pollution and the soil's condition.

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CONFLICT OF INTEREST

None.

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Екологічні аспекти використання ґрунтових ферментів як індикаторів антропогенного забруднення ґрунтів

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Анотація. У сучасній епосі, коли спостерігається швидке зростання промислових секторів та урбанізація, аналіз впливу людської діяльності на активність ґрунтових ферментів набуває особливого значення. У межах цього дослідження було встановлено мету – провести оцінку впливу антропогенного забруднення на активність ферментів у ґрунті. Для досягнення поставленої мети проведено дослідження рівня активності ферментів у ґрунті у місті Кара-Балта Чуйської області Киргизької Республіки, який вимірювався за допомогою біохімічних аналізів та спеціальних ферментативних тестів. Результати досліджень показали значне розмаїття активності каталази в різних ґрунтових зразках. Деякі зразки виявляють високу активність, тоді як інші низьку. Ці відмінності можуть бути пов'язані з окислювальним стресом та здатністю ґрунтових мікроорганізмів до розкладання пероксиду водню. Аналіз уреази показав найвищу активність у ґрунтових зразках через 2 години, особливо на межі захисного бар'єру хвостосховища, вказуючи на інтенсивні хімічні реакції, особливо поблизу джерел забруднення. Дослідження також виявили різноманітність активності протеази в ґрунтовій екосистемі, де зразки з високою активністю можуть ефективніше розкладати білки порівняно зі зразками з низькою активністю. Для досягнення екологічної стійкості ґрунтових ресурсів необхідно розробити стратегію управління, включаючи моніторинг та відновлення пріоритетних ділянок з урахуванням місцевих особливостей, підтримувати біорізноманіття, застосовувати стійкі методи сільського господарства та боротися із ґрунтовою ерозією. Важливими кроками також є утворення спільноти щодо важливості ґрунтових ресурсів, фінансування досліджень, а також співпраця з місцевими органами влади, науковцями та бізнес-спільнотою. Результати дослідження можуть бути використаними при розробці стратегій запобігання негативним наслідкам забруднення ґрунтів, сприяючи покращенню екологічної стійкості, особливо для державних структур з охорони навколишнього середовища

Ключові слова: каталаза; уреаза; протеаза; екосистема; екологічна стійкість; сталий розвиток