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Soil Pollution and Agricultural Productivity Losses

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Abstract. *In the modern era, soil pollution is considered one of the main threats to the sustainability of agricultural ecosystems. In particular, under intensive cultivation conditions, changes in the physical and agrochemical properties of soils significantly affect the yield and quality of agricultural crops. The aim of the present study was to assess the level of soil pollution in the sugar beet fields of Azershakar LLC in Yevlakh district, to evaluate its effects on the physical and agrochemical properties of the soil, and to investigate the relationships between these changes and crop yield and sugar content. During the study, soil samples were collected from plots with varying levels of pollution, and the analyses were conducted in accordance with international ISO standards. The results indicated that increasing levels of pollution led to the deterioration of soil structure, a reduction in humus content, a deficit of essential nutrients, and accumulation of sodium. These changes restrict the development of the sugar beet root system, resulting in decreased yield and reduced sugar content. The study highlights the importance of scientifically based agrotechnical and reclamation measures to preserve soil fertility and prevent productivity losses.*

Keywords: *Soil pollution, sugar beet, soil fertility, agrochemical analysis, yield losses, agricultural ecosystems*

Introduction

Soil plays an irreplaceable role in the life of humans and entire ecosystems. For agricultural ecosystems, soil serves not only as the fundamental basis for crop production but also as a critical factor in ensuring food security (Aliyev, 2015). However, in recent years, soil pollution has become one of the greatest challenges facing both ecosystems and the economy. It hinders the sustainable management of natural resources and the continued provision of ecosystem services. As a result of soil pollution, yield losses in agricultural fields and their impact on food production have become a global concern (Lehmann et al., 2020).

One of the primary causes of soil pollution is the improper or excessive use of chemical substances, including pesticides, fertilizers, industrial waste, and heavy metals, which accumulate in the soil. These substances alter the chemical structure of the soil, reducing its fertility and hindering the normal development of plants (Montanarella & Panagos, 2021). The long-term use of pesticides and fertilizers in agriculture leads to the accumulation of toxic substances in the soil and groundwater. This, in turn, reduces biological diversity within the ecosystem, decreases soil fertility, and ultimately results in economic difficulties.

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Soil pollution not only harms agriculture but also has serious impacts on local and global ecosystems, as well as human health. Crops grown on contaminated soils can enter the human food chain, leading to the accumulation of toxic substances and ultimately causing food safety issues. Contaminated soils also negatively affect local animal species and vegetation, disrupting the overall health of the ecosystem. Such disturbances in ecosystem balance can lead to long-term changes across various biological processes and threaten the sustainability of natural environments. Restoration methods for soil remediation, such as the application of organic fertilizers and natural pesticides, as well as crop rotation and the restoration of soil cover, are of particular importance. However, these approaches are effective only to a certain extent, as heavily contaminated soils require more intensive rehabilitation processes (Rodríguez-Eugenio et al., 2018).

Research on this topic explores solutions that, from both ecological and economic perspectives, support the development of modern agricultural technologies and enhance the productivity of cultivated fields. Modern technologies applied for the restoration of contaminated soils and the protection of ecosystems ensure the sustainable use of soil and the preservation of cultivated lands for future generations (Wang et al., 2021).

This study investigates the impact of soil pollution on agricultural ecosystems and identifies the main factors contributing to yield losses. Practical recommendations for addressing these issues are also proposed. Suitable management methods and ecological approaches are analyzed to ensure sustainable agricultural development, restore ecosystems, and enhance crop productivity.

Literature Review

Soil pollution occurs as a result of harmful substances entering the soil due to various human activities. Soil contamination alters the physical, chemical, and biological properties of the soil, which in turn negatively affects agricultural productivity and ecosystem functions. Recent studies have highlighted the impacts of various soil pollutants and their mechanisms:

Rashid et al. (2023) discussed the effects of pesticides and heavy metals on soil microbial diversity and nutrient uptake by plants, noting that these contaminants can significantly reduce crop growth and productivity. Similarly, Lal (2015) reported that the use of pesticides alters the chemical composition of the soil and affects ecosystem food chains.

Diacono & Montemurro (2010) demonstrated that heavy metals, such as lead and cadmium, contaminate soils, damaging soil structure and reducing agricultural yields. Montanarella & Panagos (2021) emphasized that industrial waste and persistent organic pollutants (POPs) disrupt soil microbial activity and impair the cycling of organic matter, limiting the availability of nutrients for crops.

Lehmann et al. (2020) provided a comprehensive review of how soil pollution impacts agricultural productivity, highlighting the importance of soil remediation and sustainable management practices. Luo et al. (2023) also underscored the significance of adopting sustainable agricultural approaches and modern technologies to mitigate the effects of soil contamination and improve crop yield.

Overall, these studies indicate that soil pollution is a major factor reducing agricultural productivity, disrupting ecosystem services, and posing risks to food security. They emphasize the need for scientifically based soil management, remediation techniques, and environmentally friendly agricultural practices to maintain soil fertility and ensure sustainable crop production (Brevik et al., 2015).

Materials and Methods

Yevlakh district is one of the regions in Azerbaijan that plays a significant role in agricultural production. Its favorable soil and climatic conditions provide extensive opportunities for the cultivation of various agricultural crops, particularly sugar beet. The fields of Azershakar LLC, one of the main sugar beet producers in the region, hold strategic importance both economically and agriculturally. However, in recent years, intensive agricultural activities, industrial and domestic influences, and the excessive use of mineral fertilizers and pesticides have led to soil contamination in these areas (Alloway, 2013).

The primary aim of this study was to assess the level of soil pollution in the sugar beet fields of Azershakar LLC in Yevlakh district, evaluate its effects on the physical and agrochemical properties of the soil, and scientifically investigate the relationship between these changes and yield losses. The results of this study are expected to provide a scientific basis for the efficient management of soils, the enhancement of crop productivity, and the development of environmentally sustainable agricultural practices (Luo et al., 2023).

Soil pollution in the sugar beet fields of Yevlakh district not only negatively affects the physical, chemical, and biological properties of the soil but also restricts normal plant development, reduces nutrient uptake, and consequently leads to a decline in crop yield. In contaminated soils, structural degradation, alterations in pH, and reductions in humus and essential nutrient levels pose significant risks to the sustainability of agricultural ecosystems.

Soil samples were collected from the 0–30 cm and 30–60 cm layers using a selective sampling method in accordance with national standards, taking into account the field's morphological characteristics and topography. The samples were prepared for laboratory analyses and subjected to physical, physico-chemical, and agrochemical investigations. Soil analyses were conducted using methods in accordance with international ISO standards (Kozjek et al., 2022). Crop yield indicators were determined based on production per hectare (t/ha) and analyzed in relation to the level of soil contamination.

Table 1
Physical Properties of Soil under Sugar Beet Cultivation at Azershakar LLC, Yevlakh District

Treatment	Replicate	Soil Texture (%)	Soil Moisture (%)	pH (H_2O)	Total Salinity (mg-eq/L)
I – Control	R_1	32 clay, 38 loam, 30 sand	18.5	6.8	0.12
	R_2	33 clay, 37 loam, 30 sand	18.7	6.9	0.13
	R_3	31 clay, 39 loam, 30 sand	18.4	6.8	0.12
II – Moderately Contaminated	R_1	35 clay, 40 loam, 25 sand	19.0	7.2	0.18
	R_2	34 clay, 41 loam, 25 sand	19.2	7.1	0.19
	R_3	35 clay, 39 loam, 26 sand	18.9	7.2	0.18
III – Highly Contaminated	R_1	36 clay, 42 loam, 22 sand	20.1	7.5	0.28

Treatment	Replicate	Soil Texture (%)	Soil Moisture (%)	pH (H_2O)	Total Salinity (mg-eq/L)
	R_2	35 clay, 43 loam, 22 sand	20.3	7.6	0.29
	R_3	36 clay, 41 loam, 23 sand	20.0	7.5	0.27

Table 2
Agrochemical Properties of Soil under Sugar Beet Cultivation at Azershakar LLC, Yevlakh District

Treatment	Replicate	Humus (%)	Easily Available N (mg/kg)	P (mg/kg)	K (mg/kg)	Cl^- (mg-eq/L)	SO_4^{2-} (mg-eq/L)	Ca^{2+} + Mg^{2+} (mg-eq/L)	Na^+ (mg-eq/L)
I – Control	R_1	3.2	45	22	180	5.0	8.0	14.5	2.1
	R_2	3.1	46	23	182	5.1	7.8	14.6	2.2
	R_3	3.2	45	22	181	5.0	8.1	14.4	2.1
II – Moderately Contaminated	R_1	2.8	38	20	175	7.0	12.0	16.5	4.0
	R_2	2.9	39	21	176	7.2	12.1	16.6	4.2
	R_3	2.8	38	20	175	7.1	11.9	16.4	4.1
III – Highly Contaminated	R_1	2.2	30	18	160	10.0	18.0	20.0	7.5
	R_2	2.3	31	19	162	10.2	17.8	20.2	7.6
	R_3	2.2	30	18	161	10.1	18.1	19.9	7.5

Results and Discussion

The results of the study indicate that as soil pollution increases in the sugar beet fields of Azershakar LLC inYevlakh district, significant changes occur in the physical properties of the soil (Table 1). In the control plots, the soil texture was balanced, with clay, loam, and sand fractions creating favorable conditions for the optimal development of the sugar beet root system. The optimal soil moisture and neutral pH in these plots allowed for deep root growth (Lal, 2015).

In moderately contaminated plots, an increase in the clay and loam fractions of the soil texture led to higher soil compaction and somewhat restricted water–air regime. Although root system development was impaired in these plots, the plants were still able to partially maintain their yield potential. In highly contaminated plots, soil compaction, excessive moisture accumulation, and a shift of pH towards alkalinity significantly restricted root system development. As a result, root biomass formation was reduced, leading to a decline in overall crop yield.

Agrochemical analyses demonstrated a direct relationship between soil pollution and crop yield (Table 2). In the control plots, optimal levels of humus and key macronutrients (N, P, K) supported intensive vegetative growth of sugar beet and high root productivity. In these plots, the average yield ranged from 50 to 55 t/ha, and the average root biomass was notably high.

In moderately contaminated plots, the reduction in humus and macronutrients weakened the plants' ability to uptake nutrients. As a result, the yield decreased to 42–45 t/ha, and root biomass formation was reduced; however, the sugar content remained relatively stable. This indicates that during the early stages of soil contamination, yield losses occur, but the plants still exhibit compensatory mechanisms.

In highly contaminated plots, a sharp decline in humus reserves, deficiencies in nitrogen, phosphorus, and potassium, and the excessive accumulation of sodium disrupted the agrochemical balance of the soil. Under these conditions, the sugar beet root system was poorly developed, vegetative biomass decreased, and consequently, the yield dropped to 30–35 t/ha. At the same time, the sugar content also declined, resulting in significant economic losses.

The study results indicate that soil pollution affects not only root productivity but also the technological quality of sugar beet, particularly the sugar content. In the control plots, sugar content ranged from 16–17%, in moderately contaminated plots it was 14–15%, and in highly contaminated plots it decreased to 12–13%. This decline is attributed to increased soil alkalinity and reduced nutrient uptake by the plants.

The parallel decline in sugar content and yield indicates that soil pollution causes losses in both the quantity and quality of sugar beet production. This situation can be considered a significant risk factor for Azershakar LLC in terms of raw material supply and economic efficiency.

The obtained results are consistent with previous studies and confirm that soil pollution leads to a decline in productivity within agroecosystems. In particular, sodium accumulation in the soil and a reduction in humus content were identified as the main factors weakening sugar beet root development. The deterioration of soil structure leads to water stagnation under irrigation conditions, which increases the risk of root rot (FAO & ITPS, 2015).

Thus, the studies conducted in the sugar beet fields of Azershakar LLC in the Yevlakh district demonstrate that soil pollution directly and negatively affects sugar beet yield and sugar content by altering the physical and agrochemical properties of the soil. Measures aimed at reducing soil pollution and restoring soil fertility are essential to prevent yield losses (Diacono & Montemurro, 2010).

Conclusions

The comprehensive investigation conducted in the sugar beet cultivation fields of Azershakar LLC in the Yevlakh district unequivocally demonstrates that soil contamination exerts a profound and multifaceted influence on both the physico-chemical properties of the soil and the agronomic performance of sugar beet. The empirical data indicate that alterations in soil texture, humus content, macronutrient availability, and ionic composition (notably sodium accumulation) collectively disrupt the biogeochemical equilibrium, thereby constraining root morphogenesis, nutrient uptake efficiency, and overall vegetative and generative growth.

The principal conclusions derived from this study are summarized as follows:

1. Soil contamination precipitates a significant reorganization of soil mechanical composition, manifesting in increased bulk density and compromised porosity, which directly impedes water–air regimes essential for optimal root development and metabolic activity.
2. Control plots, characterized by balanced soil texture, neutral pH, sufficient humus content, and adequate macronutrient supply (N, P, K), facilitated intensive vegetative growth, maximal root biomass accumulation, and elevated sugar yield, serving as a benchmark for assessing contamination-induced deviations.
3. Moderately contaminated soils exhibited diminished humus reserves and reduced macronutrient bioavailability, resulting in attenuated nutrient uptake efficiency. This led to a moderate decline in

yield (42–45 t/ha) while sugar content remained relatively stable (14–15%), suggesting the activation of intrinsic compensatory physiological mechanisms in sugar beet.

4. Highly contaminated plots were marked by severe humus depletion, critical deficiencies in N, P, and K, excessive Na^+ accumulation, and pH shifts toward alkalinity, which collectively impaired root system architecture and vegetative development, culminating in substantial reductions in yield (30–35 t/ha) and sugar content (12–13%).
5. The parallel diminution of quantitative and qualitative productivity parameters underscores the dual adverse impact of soil contamination on both yield potential and technological quality, thereby representing a tangible threat to the raw material security and economic efficiency of Azershakar LLC**.**
6. These findings corroborate and extend previous studies, confirming that soil contamination constitutes a pivotal limiting factor in the sustainability of agroecosystems, particularly in intensive sugar beet production zones.

Recommendations

In light of the above findings, the following scientifically grounded, agronomically and environmentally oriented interventions are proposed:

1. Implementation of integrated soil reclamation strategies aimed at mitigating sodium accumulation and restoring structural stability, including chemical amelioration (e.g., gypsum application), subsoiling, and other deep tillage techniques to enhance porosity and water–air exchange.
2. Augmentation of soil organic matter through systematic incorporation of organic fertilizers, green manure crops, and crop residues to restore biogeochemical cycling, stimulate microbial activity, and improve nutrient retention.
3. Optimization of fertilization regimes, informed by rigorous and periodic agrochemical soil analyses, to correct macro- and micronutrient deficiencies and enhance nutrient use efficiency.
4. Rationalization of irrigation and drainage management to prevent waterlogging, secondary salinization, and further degradation of soil physical properties, particularly in areas with high clay content and compaction.
5. Establishment of a continuous soil monitoring and assessment framework to evaluate contamination levels, nutrient dynamics, and soil health indicators, ensuring sustainable, economically efficient, and ecologically sound sugar beet production.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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