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# ECOLOGICAL STATE OF IRRIGATED SOILS AND WAYS TO IMPROVE IT

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## SUMMARY

In the Chirchik oasis and Almalyk region of Uzbekistan, industrial activities and intensive agriculture have led to considerable contamination of irrigated soils with toxic elements. The presented study aimed to evaluate the agrochemical state of irrigated serozem and irrigated meadow soils under the influence of the JSC Maksam-Chirchik and the Almalyk Mining and Metallurgical Complex, respectively. For restoring soil fertility, a biological remediation technology including plowed-in tree leaf litter, inoculation with actinomycete strains, and introduction of earthworms took place through lysimetric experiment. Laboratory analyses over spring and autumn showed remediation treatment increased soil nutrient availability. The nitrate nitrogen rose from 16.0 mg/kg (spring) to 22.0 mg/kg (autumn), and phosphorus also increased in treated soils. The mobile potassium level decreased by autumn, likely due to crop uptake and leaching. The contaminated soils contained aluminum (up to 72.4 mg/kg) and water-soluble fluorine (up to 64.3 mg/kg) in spring, exceeding permissible limits; however, these toxic elements declined by autumn after remediation. Heavy metals (chromium and nickel) with trace amounts manifested in spring and declined to safe thresholds in autumn in polluted sites. The biological remediation technology significantly improved the soil's health by enhancing macronutrient content, promoting humus formation, and reducing the concentrations of toxic elements in the soil. The results demonstrate the technology's effectiveness in rehabilitating polluted irrigated soils and improving their ecological state.

**Keywords:** Irrigated serozem soils, irrigated meadow soils, toxic elements, trophic chain, humus, nutrient elements

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**Key findings:** The contaminated irrigated soils showed significant seasonal dynamics in nutrient content, with biological remediation increasing available nitrogen and phosphorus. The remediation technology effectively reduced the exchangeable aluminum and fluorine levels and accumulation of chromium, nickel, and persistent pesticides and improved soil fertility, demonstrating its potential for ecological restoration of irrigated soils.

## INTRODUCTION

The rapid growth of economic development and intensification of human activities are affecting the quality of the environment and causing contradiction between the ever-increasing demands of civilization and the inability of the biosphere to satisfy these demands. It also violates the soil's ecological factors, leading to disruption of the transformation of the natural cycle of elements in the soil, causing acceleration in the soil dehumification process and accumulation of chemically active compounds. Consequently, these have a significant negative impact on a sharp decrease in the composition of soil biota, variations in soil natural processes, and the soil quality environment (Zhemchuzhin, 2002).

Additionally, it becomes possible to study the influence of each element introduced from outside in the soils and use the advanced remediation methods for reducing the negative impact of toxic elements on soil quality and environment (Bashmakov and Lukatkin, 2002). The need for theoretical substantiation of practical work on the improvement of contaminated soils and those soils not used for agricultural purposes arose as a result of the biological technologies on soils contaminated with various substances (Riskieva *et al*., 2004).

In Uzbekistan and worldwide, much attention focused on soil reclamation affected by various toxic chemical elements. It is common that these chemical elements undergo releases by various industries, enterprises, and vehicles, which accumulate in the soil and arise with constant migration in the system of atmospheric air-water-soil-plant-animals, as well as human beings (Platonova and Erofeev, 2004). During cycling, the chemical substances do not completely decompose and comprise various persistent compounds, such as cadmium, nickel, mercury, arsenic, lead, and selenium, and their accumulation in large quantities in certain areas causes adverse consequences (Bakina *et al*., 2004).

Considering one of the important environmental objects, soil is the main biogeochemical shell of the globe and an essential component of the biosphere, since most of the metabolism in living organisms takes place in the soil (Trifonova and Selivanova, 2004). Soil is a biological adsorbent and also neutralizes the organic compounds for living organisms. With the household waste discarded by the community, carbon sources and other compounds accumulate in the soil, with the microorganisms later absorbing and decomposing them (Riskieva and Mirsadikov, 2005).

Various chemical compounds and all pollutants have the highest biological activity with a negative effect on beneficial organisms in the soil, including soil biogeocenosis. Past research showed pollutants spread in the biosphere and soil also occur in food products obtained through plants and animals before being consumed by humans (Bakina *et al*., 2004; Riskieva *et al*., 2004). Currently, varying amounts of organochlorine pesticides and heavy metals are evident in food products, which can cause numerous diseases in humans.

The said biotechnology consists of plowing the field, applying autumn leaf litter at the rate of 15–20 t/ha, inoculating actinomycetes, and introducing earthworms at the rate of 5–10 pieces per square meter. The development of a biological technology has emerged to enhance the self-purifying properties of soils, based on the inoculation of active strains of actinomycetes and zoofauna adapted to living in contaminated soils—earthworms. Eventually, it will reduce the negative impact of toxic compounds on soil fertility and environmental quality (Nizamov *et al*., 2023a). Leaf litter should be in the top layer of the soil, as well as covered a little with soil for the leaves not to fly away. The leaf cover serves as a source of nutrition for zoofauna and microflora and also maintains the temperature in the soil during the autumn-winter period, and reapplying it in the spring prevents earthworms from moving into the lower soil layers. During the growing season, it is necessary to maintain soil moisture and porosity (Nizamov *et al*., 2023b).

From the results of laboratory and field experiments, the soil purification and improvement depend on the type of pollution. Complete soil reclamation can be noticeable when contaminated with pesticides and nickel. However, chromium differs from these substances with its high resistance; therefore, it is necessary to reconsider the ratios of components used for chromium (Nizamov *et al*., 2023c). Although, in such cases, it is crucial to identify the nature of toxic compounds in the soil environment. Therefore, information about the interaction of toxic compounds with soil, as well as the soil-water-plant relationship, will allow us to make changes in the newly developed 'technology,' considering well these specific conditions.

## MATERIALS AND METHODS

In irrigated agriculture, the typical serozem soils, the common soil types, practically do not obtain salinization; therefore, only anthropogenic factors serve as a factor in agronomic and technogenic pollution. Based on these aspects, irrigated soils of the serozem belt were the selected object of the study.

For the regulation of the said remediation technology, this study chose the irrigated meadow soils of the Chirchik oasis under the influence of the JSC Maksam-Chirchik, distributed within Chirchik City. The research also included irrigated soils within the influence of the Almalyk Mining and Metallurgical Plant (AMMC), covered by the Almalyk City. The listed enterprises sharply differed both in products produced and the types of wastes disposed. The selected soil monoliths came from 0–30 and 30–50 cm soil layers, as distributed within the influence of industrial enterprises before their transfer to lysimeters, with the lysimeter dimension of 1 m × 1 m. With a depth of 50 cm, the lysimeter consisted of concrete mix. For restoring contaminated soils and soil fertility, the research conducted in 2013-2015 used biological technology. At the end of the growing season, the soil conditions sustained careful studies.

### Experimental design

In the experiment, the selected soil monoliths had a depth of 0–30 and 30–50 cm and soil moisture of 60% field moisture capacity. Throughout the year, ensuring constant humidity in the lysimeters succeeded, with the soil surface loose (imitation of a fallow field), and the air temperature was natural. According to the experimental design, 15 days after the experiment began, adding dried crushed tree leaves and 100 strains of earthworms (earthworm species common in local conditions) proceeded to the lysimeters, with this work repeated every two months during the experiment. In total, 40 kg (or 40 t/ha of lysimeter) of leaf litter and 2000 earthworms succeeded in adding to each lysimeter during the season.

The soil composting process ensured maintenance by constant moisture in lysimeter conditions. Chemical analyses continued based on the following methods: humus = according to Tyurin; general NPK by the colorimetric wet ashing method; digestible phosphorus according to Machigin; exchangeable potassium through flame photometry; and nitrate nitrogen by the ion-selective method. Moreover, ammonium nitrogen used Nessler's reagent, heavy metals by acid extraction, determination of quantity by the atomic absorption method, and organochlorine pesticides by chromatography. The following strains of microorganisms used in the studies were *C. Lavendulae* (strain 13), *C. Albus* (strain 47), and *C. Fradial* (strain 1).

**Table 1.** Amount of mobile forms of nutrients in soils of lysimetric experiments (mg/kg) in spring and autumn.

| No. | Soil name | Section no. | Depth (cm) | Spring | | | Autumn | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | N-NO $_3$ | $P_2O_5$ | $K_2O$ | N-$NO_3$ | $P_2O_5$ | $K_2O$ |
| 1 | Control | 1 | 0-30 | 16.0 | 45.0 | 783.3 | 22.0 | 101.3 | 280 |
| 2 | | | 30-50 | 16.0 | 22.0 | 873.6 | 9.5 | 91.5 | 275 |
| 3 | Almalyk MMC | 2 | 0-30 | 13.0 | 120.0 | 301.3 | 16.5 | 149.4 | 148 |
| 4 | | | 30-50 | 16.0 | 60.0 | 216.9 | 8.75 | 121.3 | 150 |
| 5 | JSC - Maksam-Chirchik | 3 | 0-30 | 14.2 | 22.0 | 216.9 | 8.75 | 33.3 | 118 |
| 6 | | | 30-50 | 16.0 | 15.0 | 192.8 | 10.5 | 26.7 | 110 |

## RESULTS AND DISCUSSION

For the efficacy evaluation of the developed 'Biological Technology for Restoring the Fertility of Contaminated and Weakened Soils,' the lysimeter experiment proceeded on polluted irrigated soils. This bioremediation approach involves augmenting the soil with organic matter and beneficial organisms (earthworms and actinomycete bacteria) to enhance the natural attenuation of contaminants. Reports on similar strategies based on the integration of organic amendments with earthworm activities have emerged in pollutant degradation in contaminated soils and improving soil health (Sinha *et al*., 2008). These past studies supported the premise that enriched soil biota can accelerate the detoxification of agro-industrial pollutants, thereby protecting and restoring soil fertility.

Laboratory analyses of key nutrients (N, P, and K) in the lysimeter soils during spring and autumn revealed obvious seasonal variations. In particular, available nitrate nitrogen (N–$NO_3$) in the topsoil increased from spring to autumn in all the treatments (from 16.0 to 22.0 mg/kg in the control with a 0–30 cm layer) (Table 1). Such enhancement was in prospect because leaf litter decomposition can return the nitrogen and phosphorus to the soil, replenishing fertility in the absence of crop uptake (Berg and McClaugherty, 2008). Earthworm activity likely further accelerated the nutrient cycling by releasing nutrients locked in organic matter—for instance, worms are known to enhance nitrogen mineralization through their casting and burrowing (Van Groenigen *et al*., 2014). Available phosphorus ($P_2O_5$) also tended to rise by autumn in this experiment. However, the highest P levels were evident in soils near the Almalyk mining complex (from 120.0 mg/kg in spring to 149.4 mg/kg in autumn), which can be due to both initial industrial inputs and the mineralization of added organic matter.

In the soils influenced by the Maksam-Chirchik plant, available P increased from 22.0 to 33.3 mg/kg by autumn. Potassium ($K_2O$) was an exception, and the mobile K decreased between spring and autumn in some cases (from 301.3 to 148.0 mg/kg in the Almalyk-affected soil). The decline in K may be due to leaching and fixation in the soil profile under constant moisture conditions, as no plants prevailed there to recycle the potassium. Overall, the seasonal nutrient dynamics align with known biological processes: the addition of easily degradable organic matter (leaf litter) and active soil fauna improved nutrient availability over time, particularly for nitrogen and phosphorus, which supports the current results.

Apart from considerable variations in readily available nutrients, a notable increase also appeared in the total forms of soil nutrients from spring to autumn. In all the soil variants and at 0–30 cm and 30–50 cm depths, the total NPK levels were higher at the end of the growing season (Table 2). As there was a fallow condition with no grown crop, organic matter mineralization products accumulated in the soil rather than being taken up, leading to a net gain in nutrient reserves (Smika, 1983; Campbell and Akhtar, 1990). The outcome suggested an overall improvement in soil fertility over the course of the experiment. The formation of new humus from the added leaf

**Table 2**. Amount of common forms of nutrients in soils of lysimetric experiments (%) in spring and autumn.

| No. | Soil name | Section no. | Depth (cm) | Spring | | | Autumn | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Total nitrogen | Total phosphorus | Total potassium | Total nitrogen | Total phosphorus | Total potassium |
| 1 | Control | 1 | 0-30 | 0.030 | 0.41 | 1,808 | 0.176 | 0.108 | 2.93 |
| 2 | | | 30-50 | 0.044 | 0.36 | 2.109 | 0.158 | 0.223 | 2.37 |
| 3 | Almalyk MMC | 2 | 0-30 | 0.024 | 0.61 | 1,298 | 0.101 | 0.725 | 2.37 |
| 4 | | | 30-50 | 0.034 | 0.51 | 2,892 | 0.105 | 0.743 | 2.93 |
| 5 | JSC - Maksam-Chirchik | 3 | 0-30 | 0.030 | 0.20 | 1.657 | 0.106 | 0.176 | 3.0 |
| 6 | | | 30-50 | 0.023 | 0.18 | 1,298 | 0.081 | 0.121 | 2.87 |

**Table 3**. Amount of toxicants in soils of lysimetric experiments (mg/kg) in spring.

| No. | Soil name | Section no. | Depth (cm) | Al | F | Cr | Ni | HCH | | DDE | DDT | DDD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | α | Γ | | | |
| 1 | Control | 1 | 0-30 | 44.5 | 31.0 | *not found | *not found | *not found | *not found | *not found | *not found | *not found |
| 2 | | | 30-50 | 29.7 | 31.0 | *not found | *not found | *not found | *not found | *not found | *not found | *not found |
| 3 | Almalyk MMC | 2 | 0-30 | 72.4 | 64.3 | *not found | 2.1 | *not found | 0.0001 | *not found | Traces | *not found |
| 4 | | | 30-50 | 38.2 | 47.1 | *not found | 2.2 | *not found | 0.0009 | *not found | Traces | *not found |
| 5 | JSC - Maksam-Chirchik | 3 | 0-30 | 47.1 | 51.0 | 3.0 | *not found | *not found | 0.0007 | *not found | 0.0009 | *not found |
| 6 | | | 30-50 | 42.8 | 37.4 | 3.1 | *not found | *not found | 0.0009 | *not found | 0.0009 | *not found |

*Note: *not found - not detected.*

litter and its incorporation into the soil profile likely contributed to the enhanced total nutrient content. Sustained fallow periods typically promote the build-up of soil nitrate and other nutrients through continued decomposition of organic residues (Smika, 1983; Campbell and Akhtar, 1990), and these findings were consistent with the increased soil nutrients observed in the presented study. Thus, by autumn the soils had a higher stock of nutrients and organic matter, indicating that the present biotechnological treatment aids in contaminant removal as well as promotes nutrient cycling and soil structure.

In addition to nutrient dynamics, the behavior of toxic inorganic contaminants (heavy metals and fluorine) entailed monitoring in polluted soils. The spring-season analysis showed elevated levels of these elements in the topsoil, reflecting the legacy of industrial emissions. The exchangeable aluminum in the 0–30 cm soil layer reached toxic concentrations—72.4 mg/kg in the Almalyk MMC-affected soil, and even the control soil contained 44.5 mg/kg Al—indicating some background aluminum toxicity. Water-soluble fluorine (fluoride) was also high, and the control soil had about 31 mg/kg F (approximately three times the maximum allowable concentration, MAC), while soils near Almalyk contained 64.3 mg/kg F. Likewise, in the zone influenced by the Maksam-Chirchik chemical plant, fluoride reached 51 mg/kg (≈5.8 MAC) (Table 3). The presented results were greatly analogous to past reports that heavy metal pollutants tend to accumulate in the upper soil horizons near their source of input (Platonova and Erofeev, 2004).

Industrial activities, such as metal smelting and phosphate fertilizer production, are well-known for releasing heavy metals and fluoride into the surrounding environment, leading to contaminated topsoil. High soil fluoride, in particular, has been evident to disrupt the soil biota and organic matter decomposition (Zhu *et al*., 2007), leading to the decline in soil quality. The co-occurrence of toxic metals (aluminum, chromium, and nickel) and other deleterious elements (fluorine) is a serious environmental concern, as soil can act as a sink and a source of these contaminants for plants and groundwater (Khan *et al*., 2010). In the promising study, mobile forms of chromium and nickel entailed detection in the samples collected in the spring of the polluted variants, i.e., Cr (Maksam-Chirchik soil) and Ni (Almalyk soil); however, these elements were nonexistent in the uncontaminated control soil. This pattern of localized contamination has the expectation to occur near industrial sites and has also had reports in other polluted agroecosystems (Platonova and Erofeev, 2004; Khan *et al*., 2010). Accumulation of heavy metals and fluorine in surface soils under industrial influence corroborates past findings and underscores the need for remediation to prevent their entry into the food chain.

Notably, under biological remediation treatment and after one growing season, the contaminant levels significantly decreased in the soil. By autumn, the exchangeable Al had dropped compared to spring in all variants, and water-soluble fluoride was also much lower (Table 4). Furthermore, the trace amounts of mobile chromium and nickel observed during spring virtually disappeared by autumn, and their concentrations fell well below maximum permissible limits in the treated soils. These improvements revealed the introduced actinomycetes, earthworms, and leaf litter had a positive impact on reducing pollutant availability. Decomposing organic matter usually raises the soil pH and supplies binding sites, which can immobilize the metals like aluminum and mitigate their toxicity (Haynes and Mokolobate, 2001). In similar conditions, past studies have shown that adding organic residues or the amendments can precipitate the aluminum into less harmful forms, thereby ameliorating aluminum stress in soil (Haynes and Mokolobate, 2001).

Earthworms and microbes with enhanced biological activities also likely contributed to the contaminants' decline. Earthworms can inherently sequester heavy metals in their tissues, transforming metals into more stable fractions in the soil (Sizmur and Hodson, 2009). Their findings further revealed earthworm activity decreased the bioavailability of metals by mixing the soil and promoted adsorption of metals onto organic and mineral particles. Similarly, other studies enunciated earthworms can accumulate metals like Cd, Pb, Ni, and Zn through metallothioneins, effectively acting as biological filters in contaminated soils (Usmani

**Table 4.** Amount of toxicants in soils of lysimetric experiments (mg/kg) in autumn.

| No. | Soil name | Section no. | Depth (cm) | Al | F | Cr | Ni | HCH | | DDE | DDT | DDD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | α | γ | | | |
| 1 | Control | 1 | 0-30 | 42.1 | 29.0 | *not found | *not found | *not found | *not found | *not found | *not found | *not found |
| 2 | | | 30-50 | 27.2 | 22.7 | *not found | *not found | *not found | *not found | *not found | *not found | *not found |
| 3 | Almalyk MMC | 2 | 0-30 | 67.9 | 63.5 | 1.5 | 2.1 | Traces | Traces | *not found | *not found | *not found |
| 4 | | | 30-50 | 34.7 | 30.1 | 1.0 | 2.7 | Traces | Traces | *not found | *not found | *not found |
| 5 | JSC - Maksam-Chirchik | 3 | 0-30 | 41.0 | 47.2 | 3.0 | 1.8 | 0.0001 | 0.0001 | *not found | 0.009 | *not found |
| 6 | | | 30-50 | 39.9 | 35.1 | 3.8 | 1.8 | Traces | Traces | *not found | *not found | *not found |

and Kumar, 2015). In the latest experiment, the decrease in exchangeable Al and soluble F could also refer to gradual leaching under maintained moisture conditions, while the organic matter and soil biota present would have helped retain these elements in less soluble forms. Overall, in autumn the reduction of aluminum, fluoride, and heavy metal mobility demonstrates the effectiveness of the bioremediation measures in improving the soil's ecological state. The encouraging results align with previous findings that integrating organic amendments and soil fauna can remove the heavy metal contaminants from the soil (Sinha *et al*., 2008; Haynes and Mokolobate, 2001).

The tracking of residual organochlorine pesticides, which are persistent organic pollutants, also ensued in the studied soils. In spring, the α-isomer of hexachlorocyclohexane (α-HCH-hexachlorocyclohexane) was non-emergent in any soil variant, with only trace amounts observed in autumn. The more toxic γ-HCH (lindane) appeared with very low concentration in the industrially influenced soils during spring (10^−4–10^−3 mg/kg); however, in autumn it had virtually disappeared from the studied soils. Dichlorodiphenyltrichloroethane (DDT) and its metabolites (DDE—dichlorodiphenyldichloroethylene and DDD—dichlorodiphenyldichloroethane) did not occur in the lysimeter soils at any significant level, and in a few cases, a barely detectable trace of DDT emerged. In the presented experiment, the rapid attenuation of HCH isomers and absence of DDT residues suggest that active biodegradation took place over the course of the season. Previous studies have documented that soil microorganisms, particularly certain bacteria and actinomycetes, can degrade organochlorine pesticides effectively under favorable conditions (Alvarez *et al*., 2017). For instance, Zhemchuzhin (2002) reported the native microbial community's role in detoxifying agrochemicals and persistent pesticides in soil. In a previous study, Alvarez *et al*. (2017) noted various actinobacteria genera (*Streptomyces, Rhodococcus,* and *Arthrobacter*) emerged to use organochlorine compounds as carbon sources and mineralize them naturally.

In this study, the inoculation with active actinomycete strains in integration with adding organic substrate (leaf litter) and earthworms developed conditions conducive to pesticide biodegradation. Actinomycetes usually produce a wide array of extracellular enzymes that can dehalogenate and decompose stable organic pollutants, including HCH and DDT, thereby accelerating their dissipation in soil (Alvarez *et al*., 2017). Additionally, earthworms can improve aeration and distribute microbes and nutrients, further facilitating the breakdown of such compounds (Sinha *et al*., 2008). The near-complete removal of HCH isomers by autumn in present lysimeters proved consistent with past findings on bioremediation. It demonstrates the enhanced self-purification capacity of the soil by amending it with a combination of detritus (leaf litter) and pollutant-degrading biota. Overall, the disappearance of detectable organochlorine pesticide residues in the latest experiment provides considerable evidence that the biological treatment effectively promoted the degradation of these toxic chemicals, protecting the soil, and aligning with reported cases of successful pesticide bioremediation (Alvarez *et al*., 2017; Zhemchuzhin, 2002).

Overall, the lysimetric experiment results confirmed that the proposed biological remediation technology substantially improves the ecological state of contaminated irrigated soils. The seasonal increase in nutrient availability and total nutrient content revealed the restoration of soil fertility, likely through enhanced nutrient cycling and humus formation. Concurrently, the marked reduction in toxic elements (heavy metals and fluoride) and the degradation of persistent pesticides demonstrate the soil's regained self-reclamation capacity. These results acquired support from numerous studies of bioremediation, which also reported similar trends of improved soil health by using organic amendments and soil biota for remediation (Haynes and Mokolobate, 2001; Van-Groenigen *et al*., 2014; Alvarez *et al*., 2017). By inoculation of actinomycetes and the introduction of earthworms, in addition to organic matter, they emerged as an effective strategy to rehabilitate polluted soils. This bio-augmented approach not only mitigates the concentrations of hazardous substances but also promotes nutrient enrichment and soil biological activity, leading to a more balanced and resilient soil ecosystem.

## CONCLUSIONS

Soil contamination from industrial emissions and intensive agriculture poses a serious threat to soil fertility and environmental health. A biological remediation technology using leaf litter, earthworms, and actinomycete inoculation effectively restored the fertility of contaminated irrigated soils. The treated soils showed increased nutrient availability and enhanced humus formation, indicating improved soil quality and productivity potential. The technology significantly reduced the bioavailability of toxic elements: exchangeable aluminum and water-soluble fluorine levels decreased, and mobile forms of heavy metals (Cr, Ni) and persistent pesticides (HCH, DDT) either disappeared or reduced to safe levels. The biological approach considerably improved the ecological state of polluted soils, offering an effective and eco-friendly solution for soil remediation.

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