DOI: 10.12731/2658-6649-2025-17-6-2-1532 **EDN: WJMYSA**
UDC 63: 58.07

Original article

THE IMPACT OF AGRICULTURAL ACTIVITY ON SOIL PHYTOTOXICITY: THE CHOICE OF BIOINDICATORS

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Abstract

Background. The study is devoted to the assessment of phytotoxicity of soils affected by agricultural activities by the method of bioindication. The main objective is to select the most sensitive bioindicator for the determination of phytotoxicity in agricultural soils. It was found that cruciferous crops, *Brassica napus* (rapeseed), *Lepidium sativum* (watercress), are the most sensitive to contamination, demonstrating a decrease in germination to 24% and phytomass to 0.13-0.62 g, while barley showed a germination resistance of 70-100%. Cases of latent phytotoxicity have been identified with preserved germination, but inhibition of root growth. The results confirm the effectiveness of the method and the need for an integrated approach using several bioindicators.

Purpose. The purpose of this study is to select the most sensitive bioindicator for determining the phytotoxicity of agricultural soils.

Materials and methods. To assess the phytotoxicity of soils, samples were taken from the DSTU training ground. The main series included 4 arable samples (n=4), selected by the envelope method from a depth of 0-20 cm according to GOST 17.4.4.02-2017. The control sample was taken from the adjacent forest belt (n=1). Each combined sample weighing 1 kg was formed from 5-point samples. Four test crops were used: radish (*Raphanus sativus L.*), barley (*Hordeum vulgare L.*), rapeseed (*Brassica napus L.*) and watercress (*Lepidium sativum L.*). 3 analytical replications in Petri dishes were prepared for each sample and culture. Incubation was carried out for 10 days. The following parameters were evaluated: germination (%), germination energy (%), length of shoots and roots (mm), crude phytomass (g). Statistical data processing was performed with the calculation of average values and standard deviation for each sample and test culture.

Results. The results have shown a significant inhibition of the test plant growth in contaminated samples, which resulted in a decrease in key indicators by 24-92% compared with the control. Cruciferous crops (rapeseed and watercress) showed the greatest sensitivity, with a sharp decrease in germination to 24%, germination energy to 1.0, and phytomass to 0.13-0.62 g. At the same time, barley has demonstrated relative stability, maintaining germination at the level of 70-100%, which confirms the need to use several bioindicators for a comprehensive assessment.

Conclusion. During the study, it was found that agricultural activity in the field under study led to the formation of phytotoxicity of the soil, manifested in the suppression of sensitive cruciferous crops (rapeseed, watercress) and the radish root system. Rapeseed and watercress are highly sensitive bioindicators for monitoring. The revealed heterogeneity of phytotoxicity requires a differentiated approach to assessing soil conditions. The conducted studies have demonstrated the effectiveness of the phytoindication method for assessing the phytotoxicity of soils exposed to agrogenic effects.

Keywords: soil phytotoxicity; bioindication; phytotesting; cruciferous crops; environmental monitoring

For citation. Dubnitskaya, P. A., Ligacheva, V. S., Mun, E. A., Polyakov, A. G., & Odabashyan, M. Yu. (2025). The impact of agricultural activity on soil phytotoxicity: The choice of bioindicators. *Siberian Journal of Life Sciences and Agriculture*, *17*(6-2), 341-360. https://doi.org/10.12731/2658-6649-2025-17-6-2-1532

Научная статья

ВЛИЯНИЕ СЕЛЬСКОХОЗЯЙСТВЕННОЙ ДЕЯТЕЛЬНОСТИ НА ФИТОТОКСИЧНОСТЬ ПОЧВ: ВЫБОР БИОИНДИКАТОРОВ

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Аннотация

Обоснование. Исследование посвящено оценке фитотоксичности почв подверенной влиянию сельскохозяйственной деятельности методом биоиндикации. Установлено, что крестоцветные культуры, Brassica *napus* **(**рапс), *Lepidium sativum* (кресс-салат), наиболее чувствительны к загрязнению, демонстрируя снижение всхожести до 24% и фитомассы до 0,13-0,62 г, тогда как ячмень показал устойчивость всхожесть 70-100%. Выявлены случаи скрытой

фитотоксичности при сохранной всхожести, но угнетении роста корней. Результаты подтверждают эффективность метода и необходимость комплексного подхода с использованием нескольких биоиндикаторов.

Цель. Целью исследования – подбор наиболее чувствительного биоиндикатора для определения фитотоксичности почв сельскохозяйственного назначения.

Материалы и методы. Для оценки фитотоксичности почв были отобраны пробы с учебно-опытного полигона ДГТУ. Основная серия включала 4 пахотные пробы (n=4), отобранные методом конверта с глубины 0-20 см согласно ГОСТ 17.4.4.02-2017. Контрольный образец взят из прилегающей лесополосы (n=1). Каждая объединенная проба массой 1 кг формировалась из 5 точечных проб. Использовали четыре тест-культуры: редис *(Raphanus sativus L.),* ячмень *(Hordeum vulgare L.),* рапс *(Brassica napus L.)* и кресс-салат *(Lepidium sativum L.).* Для каждого образца и культуры подготовили по 3 аналитические повторности в чашках Петри. Инкубацию проводили 10 суток. Оценивали следующие параметры: всхожесть (%), энергию прорастания (%), длину побегов и корней (мм), сырую фитомассу (г). Статистическую обработку данных выполняли с расчетом средних значений и стандартного отклонения для каждой пробы, и тест-культуры.

Результаты. Результаты показали значительное угнетение роста тест-растений в загрязненных образцах, что выражалось в снижении ключевых показателей на 24–92% по сравнению с контролем. Наибольшую чувствительность проявили крестоцветные культуры (рапс и кресс-салат), у которых зафиксировано резкое снижение всхожести до 24%, энергии прорастания до 1,0 и фитомассы до 0,13–0,62 г. В то же время ячмень продемонстрировал относительную устойчивость, сохраняя всхожесть на уровне 70–100%, что подтверждает необходимость использования нескольких биоиндикаторов для комплексной оценки.

Заключение. В ходе исследования было установлено, что сельскохозяйственная деятельность на исследуемом поле привела к формированию фитотоксичности почвы, проявляющейся в угнетении чувствительных крестоцветных культур (рапс, кресс-салат) и корневой системы редиса. Рапс и кресс-салат являются высокочувствительными биоиндикаторами для мониторинга. Выявленная неоднородность фитотоксичности требует дифференцированного подхода к оценке состояния почв. Проведенные исследования продемонстрировали эффективность метода фитоиндикации для оценки фитотоксичности почв, подверженных агрогенному воздействию.

Ключевые слова: фитотоксичность почв; биоиндикация; фитотестирование; крестоцветные культуры; экологический мониторинг

Для цитирования. Дубницкая, П. А., Лигачева, В. С., Мун, Е. А., Поляков, А. Г., & Одабашян, М. Ю. (2025). Влияние сельскохозяйственной деятельности на фитотоксичность почв: выбор биоиндикаторов. *Siberian Journal of Life Sciences and Agriculture*, *17*(6-2), 341-360. https://doi.org/10.12731/2658-6649-2025-17-6-2-1532

Introduction

Modern agriculture, being the basis of food security, has an intense and multifactorial impact on soil ecosystems. The use of mineral fertilizers, pesticides, ameliorants, the use of heavy machinery, intensive tillage and monoculture agriculture lead to complex changes in the physico-chemical and biological properties of soil. In order to control the influence level of the above listed anthropogenic factors on agroecosystems, environmental monitoring is used. Currently, it is based on physical and chemical methods that make it possible to quantify the content of pollutants and compare them with established standards, such as maximum permissible concentrations (MPC) [1]. However, this approach has significant limitations, since MPCs do not take into account the complex effects on ecosystems, their ability to accumulate in food chains and cause long-term consequences [1]. As a result, the data obtained exclusively by physical and chemical methods are insufficient to predict environmental risks [1]. In this regard, biomonitoring, based on the assessment of the reaction of living organisms to anthropogenic impact, is becoming increasingly important. Biological methods are highly sensitive, allowing them to detect negative changes even at low concentrations of pollutants, and provide a more integrated assessment of the state of ecosystems compared to instrumental analyses [2].

A special place in environmental monitoring is occupied by the assessment of soils, which play a key role in the functioning of ecosystems. For agricultural lands, fertility is a key criterion – the ability of the soil to provide plants with nutrients, moisture, and optimal physical and chemical conditions. Fertility determines crop yields and biological productivity of natural vegetation, while natural and artificial fertility created by agrotechnical techniques are distinguished. Depending on productivity, arable land is classified into highly productive more than 5 tn/ha, medium-productive 3-4 tn/ha, unproductive 1-2 tn/ha and unsuitable for agriculture less than 1 tn/ha.

One of the most effective methods of assessing the ecological state of soils is biotesting, based on the use of standardized test organisms to detect toxic, mutagenic or other harmful effects [1]. Unlike chemical analysis, biotesting makes it possible to assess the integral toxicity of the soil, taking into account

the combined effect of all pollutants, including those whose concentrations are below the detection threshold of the devices. An important advantage of this method is its ability to detect negative changes at an early stage, before the appearance of visible disturbances in the ecosystem [1].

Seeds of higher plants such as cress (*Lepidium sativum*), yellow mustard (*Sinapis alba*) and sorghum (*Sorghum saccharatum*) are widely used as test objects. Criteria of phytotoxicity are indicators of germination (germinating capacity, germination energy) and development of germinating seedlings (length and weight of roots, aboveground part). Small-seeded crops with a limited supply of nutrients are more sensitive to contamination, which makes them convenient bioindicators.

At the same time, the soil is a complex object for biotesting due to its heterogeneity and high content of organic and mineral components. The reliability of the results is influenced by sampling methods, test conditions, and the choice of test organisms. Therefore, for a comprehensive assessment of soil conditions, it is recommended to combine biological methods with physical and chemical analysis, which allows obtaining the most complete information about their ecological condition and potential risks to the environment.

Based on this, the relevance of this work lies in the fact that agrochemical analyses cannot predict changes in agroecosystems, and cannot show the effect of a particular compound on a plant, which underlines the need for biomonitoring to identify deviations in ecosystems. Timely identification of problems will help prevent critical situations and maintain high yields.

Phytotoxicity of the soil is its property to have a sparing effect on higher plants, which causes the presence of pollutants and toxins in the soil. Phytotoxicity leads to disruption of physiological processes, suppression of plant growth and development, resulting from increased accumulation of physiologically active substances, including phenolic compounds, organic acids, aldehydes, alcohols, etc. [3]. The source of toxic substances in the soil is the root secretions of plants, post-harvest plant residues, products of microbial metabolism, as well as residual products from fertilizers and plant protection products. Phytotoxic substances accumulate most actively during the development of anaerobic conditions in the soil and during the cultivation of homogeneous or biologically similar crops in one place. Root secretions secreted by plants or pathogens are highly toxic. They contain 15 groups of water-soluble organic substances, including alkaloids, coumarins, cinnamic acid, quinones, terpenoids, flavonoids, tannins, and many other compounds [4]. The following factors influence the formation of general phytotoxicity of soils: the content of heavy metals in the soil by 39%, soil factors by 34%, the content of pesticides by 22%, and saturation of crop rotation with grain crops by 5% [4].

Heavy metals (HMs) are one of the most dangerous pollutants, the main sources of entry into uncontaminated soils of which are quarries and mines for the extraction of polymetallic ores, metallurgical enterprises; vehicles, chemical means of protecting crops from diseases and pests. Also, the impact of gas and dust emissions from industrial enterprises extends over a distance of 50 km or more from the city limits. It is important to take into account that HMs can be absorbed by plants not only from the soil, but also directly from the atmosphere (cadmium, lead), which poses a great danger of accumulation of toxic substances in plants that are grown in fields located in the zone of influence of the city. HMS also play the role of an ecotoxicological factor that determines the direction and nature of the development of soil cenosis, which can be observed both when soils are contaminated with heavy metals in high concentrations once, and with systematic contamination with small doses, which is much more common. The consequences of this pollution can be toxicosis of plants, animals and humans [3].

Another of the most dangerous and frequently encountered pollutants are pesticides. Their use leads to a restructuring of the ecological situation in the soil, changing its microbiocenosis inhibiting some groups of microorganisms and stimulating the reproduction of others, whose representatives are able to produce phytotoxic substances and thereby exacerbate the negative effects of the drugs used. Even the complex use of pesticides in recommended doses provokes a decrease in the number of ammonifying bacteria, a shift in the microcenosis of cellulose-destroying microorganisms in the soil occurs. Pesticides not only cause soil toxicity, but also accumulate in the root system and final products, which leads to environmentally inferior products [4].

To assess the phytotoxicity of soils resulting from agricultural activities, various biotesting methods are used to determine the reaction of test plants to the presence of toxicants.

The seedling method is based on the analysis of the reaction of plant seeds to polluted soil. The seeds are sown in Petri dishes with soil selected from various sites, and the germination rate, germination energy, length of the root and aboveground parts, as well as the weight of the dry matter of the seedlings are monitored [5].

The contact method is the placement of test crop seeds directly on moistened soil plates, without prior preparation of an aqueous extract. It allows us to assess the cumulative effect on plants of both water-soluble compounds and substances adsorbed on soil particles.

This approach is one of the most informative for rapid assessment of the general toxic background of the soil [8].

The initiated microbial community (IMC) method is a modified version of the contact method. The method is based on the artificial creation of a microbial community on the surface of sterilized soil plates. To do this, starch, agar-agar, or any other substrate that is nutritious for microorganisms is applied to the soil, after which the samples are incubated under optimal humidity and temperature conditions. During this time, an active microbial community has formed on the soil surface. Next, seeds of test plants are placed on the grown colonies of microorganisms and their germination and seedling development are analyzed. Comparing the results with ordinary soil plates (without IMS), the role of the biogenic factor can be assessed. If the difference between the variants is significant, it means that the phytotoxicity is more due to the activity of microorganisms. If the differences are minimal, then the main negative impact is associated with accumulated chemical pollutants in the soil [2].

The eluant phytotesting method consists in analyzing the toxicity of aqueous extract (eluate) of soils. Its essence is the assessment of the impact of water-soluble pollutants on indicator plants. The seeds were germinated in Petri dishes on filter paper soaked in an aqueous extract of the sample, and the control group in distilled water. After 3-7 days, the length of the roots of the seedlings and the germination of the seeds are measured [9, 10].

Criteria for selecting test objects for assessing phytotoxicity include germination rate, sensitivity to pollutants, representativeness for the studied region, and diversity of functional groups. The international standard ISO 11269-2 regulates the selection of at least two plant species, one monocotyledonous and the other dicotyledonous.

Examples of bioindicators. In the course of the development of science, as knowledge about changes in the biochemical state of plants and the ecological and geochemical state of soils increased, the term "biological monitoring" was formed, the essence of which is to study the state of air, water and soil environments based on the results of the analysis of the reaction of living organisms [13]. In direct proportion to the increase in the impact of anthropogenic impact, the importance of environmental monitoring, of which biological monitoring is a part, is growing.

Bioindicators are living organisms or a community of organisms whose presence, condition, and behavior determine bioecotopic changes in the environment. Various macro-organisms and microorganisms, including plants, can act as bioindicators. Based on the type of reaction to the content of elements in the environment, accumulators are isolated – plants that accumulate pollutants, indicators that reflect the current state and plants that exclude the transfer of metal from the environment. When diagnosing pollution of environmental

components by various pollutants, plants with a reliably known reaction to their effects are used, lettuce, shoot-forming vole, common pine, hanging birch, and dioecious nettle are widely used [13; 14; 16].

Together with the harvest, a certain amount of nutrients is removed from the soil, to replenish which fertilizers are applied. For reasons of economy, crude or insufficiently purified fertilizers can be used, which contain heavy metals as trace substances that are inactive in the soil environment [13].

The introduction of excessive amounts of fertilizers leads to the fact that most of them, being absorbed by plants, at the same time cannot be included in the metabolic processes. For example, when an excess amount of saltpeter is added to the soil, nitrates accumulate in the upper parts of plants, most of them turn into nitrites, which are toxic salts for living organisms [13].

These examples of negative impacts threaten not only human health, but also the stability of agroecosystems, as the circulation of organic substances is disrupted, the soil structure and demoecological indicators of populations in cultivated areas are changing. This determines the relevance of biological monitoring [13; 15; 17].

Bioindicator plants have a number of advantages: they are widespread, relatively easy to cultivate, and have clear and measurable responses to pollutants (for example, changes in biomass, physiological parameters, and accumulation of pollutants in tissues).

Radish is often used as a bioindicator, due to its sensitivity to various factors of the soil environment and the precocity of the crop. The rapid growth and short growing season of radishes make it possible to get results quickly. Radishes accumulate heavy metals, which leads to visible changes in morphology: contamination can lead to changes in the size of root crops, their shape, the formation of necrotic spots on the leaves, etc., which is an advantage of this plant as a bioindicator. Its disadvantages include sensitivity to abiotic factors (temperature, humidity) and relatively low biomass.

Rapeseed is an oilseed crop with high adaptability to various types of soils. The advantages of rapeseed as a bioindicator include: high biomass, which makes it possible to obtain a sufficient amount of material for analysis, the ability to accumulate heavy metals in seeds and other organs, and some varieties can be used for phytoremediation [17]. However, rapeseed has a longer growing season compared to radishes and microgreens, which slows down the results.

Microgreens are sprouts of various vegetable and grain crops harvested at the stage of the first true leaves. It has a high nutritional value, which simplifies the analysis of heavy metal content, high growth, which allows obtaining results within a few days, and the ability to grow under controlled conditions, which

minimizes the influence of external factors [18; 19]. These properties make microgreens a promising object for biological monitoring. The disadvantages of microgreens as a bioindicator include low biomass.

Materials and Methods

The soil samples for the study were obtained from the educational and experimental landfill of the Don State Technical University. The main series is represented by 4 samples (n=4) selected by the envelope method from an arable field subjected to regular agricultural processing. Each combined sample is formed from 5-point samples taken from a depth of up to 20 cm in accordance with the requirements of GOST 17.4.4.02-2017 "Nature Protection. Soils. Methods of sampling and preparation of samples for chemical, bacteriological, helminthological analysis" (GOST – Russian National Standard). The control sample (n=1) was selected by a similar method from the adjacent forest belt, considered as a zone with minimal anthropogenic impact. The total weight of each sample was approximately 1 kg.

The samples were transported to the laboratory in an inert polyethylene container. Preparation was carried out in the laboratory: foreign inclusions, roots, stones, and macrofauna were removed. For biotesting, analytical samples weighing 25.0±0.1 g were selected from each sample of arable soil and control.

Phytotoxicity assessment was carried out by direct germination of seeds on a soil substrate in accordance with the principles of GOST R ISO 22030-2009 "Soil quality. Biological methods. Chronic phytotoxicity in relation to higher plants". A 25.0 g soil sample was placed in sterile Petri dishes. The soil is evenly moistened with 25 ml of tap water soil:water ratio = 1:1, which provided optimal moisture for seed germination without flooding.

The following types of bioindicators were used:

1. Radish Raphanus sativus L., a precocious variety.
2. Spring barley *Hordeum vulgare* L.
3. Spring rapeseed *Brassica napus* L.
4. Watercress salad *Lepidium sativum* L.

3 analytical replications of Petri dishes were prepared for each test crop and each soil sample (4 arable + 1 control). The optimal number of seeds of the selected crop was sown in each cup, based on their size, which had not previously been etched. The number of radish seeds is 25, barley-30, rapeseed-55, lettuce - 50. Petri dishes are labeled, covered with lids to maintain moisture and placed in the laboratory under an ultraviolet lamp.

Incubation lasted 10 days under strictly controlled conditions: temperature: 22±1°C; relative humidity: 70±5%.

1. Seed germination (%): The number of germinated seeds was recorded daily; the germination criterion was the appearance of a root ≥ 2 mm long. The final germination was calculated on the 10th day relative to the total number of sown seeds according to GOST 12038-84 "Seeds of agricultural crops. Methods for determining germination".

2. Germination energy (%). It was calculated as the percentage of seeds germinated in the first 3 days for radishes and watercress, and 4 days for barley and rapeseed, taking into account the specific features of the germination rate.

3. Morphometric parameters of seedlings (mm): On the 10th day, the length of the hypocotyl/coleoptile and the length of the primary root of each seedling in the Petri dish were measured. No measurements were performed for the root system of barley, where root accretion was observed.

4. Crude phytomass (g): On the 10th day, all seedlings in each cup, analytical repeat, were cut off with a scalpel at the substrate level. The aboveground part, the phytomass, was immediately weighed on an analytical balance with an accuracy of 0.001 g to determine the crude mass.

Statistical data processing. For each measured parameter (Germination, Germination energy, Average shoot length, Average Root length, Crude phytomass) The arithmetic mean and standard deviation were calculated for each soil sample and test culture based on three analytical repetitions. A graphical visualization of the results is presented in Table 1.

Table 1.

Results of germination of test objects

	Radish	Barley	Rapeseed	Watercress salad
Germination%	84	90	60	63
	80	70	60	45
	72	100	48	56
	76	100	24	42
	76	100	60	45
Control	84	83	24	67
The average value	79.3	90.5	46.0	53.0
Standard deviation, %	4.8	11.2	16.4	9.5
Seedling vigor	2.1	2.3	2.5	2.9
	2.0	1.75	2.1	2.1
	1.8	2.5	2.0	2.6
	1.9	2.5	1.0	1.9
	1.9	2.5	2.5	2.1

Control	2.1	2.1	1.0	3.1
The average value	1.9	2.3	1.9	2.5
Standard deviation, %	0.1	0.3	0.7	0.5
Phytomass, g	2.5	3.2	0.1	0.2
	2.7	2.9	0.4	0.1
	1.5	2.5	0.6	0.1
	2.2	2.3	1.2	0.4
	2.3	3.4	0.4	0.3
The average value	2.2	2.9	0.5	0.2
Standard deviation, %	0.5	0.4	0.4	0.1
Length of the green part, mm	Max= 60 Min= 25	Max= 150 Min= 10	Max= 22 Min= 5	Max= 30 Min= 5
	Max= 80 Min= 21	Max= 190 Min= 45	Max= 80 Min= 12	Max= 35 Min= 20
	Max= 70 Min= 25	Max= 170 Min= 20	Max= 32 Min= 10	Max= 40 Min= 15
	Max= 70 Min= 29	Max= 170 Min= 23	Max= 35 Min= 4	Max= 35 Min= 15
Control	Max= 87 Min= 35	Max= 195 Min= 31	Max= 65 Min= 30	Max= 30 Min= 17
The average value	Max= 73,4 Min= 27,0	Max= 175,0 Min= 25,8	Max= 46,8 Min= 12,2	Max= 34,0 Min= 14,4
The length of the roots, mm	Max= 115 Min= 10	The roots fused into one ecosystem, measurement was not possible.	Max= 40 Min= 15	Max= 35 Min= 15
	Max= 40 Min= 25		Max= 100 Min= 5	Max= 50 Min= 25
	Max= 90 Min= 73		Max= 30 Min= 40	Max= 40 Min= 5
	Max= 45 Min= 15		Max= 30 Min= 30	Max= 50 Min= 6
	Max= 120 Min= 51		Max= 40 Min= 1	Max= 30 Min= 5
Control	Max= 115 Min= 1		Max= 15 Min= 10	Max= 50 Min= 40
The average value	Max= 87.5 Min= 29.2		Max= 42.5 Min= 16.8	Max= 42.5 Min= 16.00

The presented methodology, based on the principles of GOST R ISO 22030-2009 and GOST 32640-2014, provided a comprehensive assessment of the phy-

totoxicity of soils in the arable field of DSTU landfill in comparison with the background control of the forest belt. The use of a standardized phytotest with four test cultures (*Raphanus sativus L., Hordeum vulgare L., Brassica napus L., Lepidium sativum*) and three analytical replicates per sample allowed us to obtain representative data on key biometric indicators. The analysis of the results confirms the logic of the chosen approach:

1. The data show marked differences in the response of test objects to agrogenic effects. For example, the indicators of barley: germination 70-100%, germination energy 1.7-2.5, phytomass 2.4-3.4 g in arable samples are often comparable or slightly different from the control: germination 83-100%, energy 2.08-2.5, phytomass 2.0-3.0 g, indicating its relative tolerance. At the same time, rapeseed and watercress showed high sensitivity: rapeseed in arable samples showed a sharp decrease in germination to 24%, germination energy to 1.0 and phytomass to 0.13 g relative to the control: germination 60%, energy 2.5, phytomass 1.20 g.

2. The results on the length of roots and shoots revealed inhibition of growth, which does not always correlate with a decrease in germination. Thus, watercress in individual arable samples with a relatively high germination rate of 45-67% showed a critical suppression of root length (Mp=5 mm versus Mp=40 mm in the control) and phytomass of 0.09-0.19 g versus 0.35 g in the control, which emphasizes the importance of evaluating these parameters to identify latent phytotoxicity.

3. Standardized incubation conditions and consideration of parameters, germination, germination energy, length of shoots / roots, phytomass, in accordance with GOST 12038-84 ensured reproducibility of the results.

Thus, the integrated phytotesting approach used has proven effective in identifying and quantifying the phytotoxicity of agrogenically disturbed soils, providing reliable data for subsequent analysis of the causes of the observed suppression of test crops. The results obtained substantiate the applicability of the selected bioindicators and accounting parameters for monitoring the state of agricultural soils. Agricultural activity in the studied field of DSTU landfill led to the formation of soil phytotoxicity, manifested in significant suppression of sensitive cruciferous crops (rapeseed, watercress) and the radish root system. Rapeseed and watercress, especially in terms of root length and phytomass, are highly sensitive bioindicators for monitoring. The revealed spatial heterogeneity of phytotoxicity requires a differentiated approach to assessing soil conditions and developing remediation measures.

Results and discussion

There are differences in the reaction of test objects to agrogenic effects, which confirms the need to use several different bioindicators for a comprehen-

sive assessment of soil phytotoxicity. Indicators of rapeseed and microgreens indicate the manifestation of high sensitivity

There is an inhibition of the growth of shoots and roots, which does not always correlate with a decrease in germination. In microgreens in individual arable samples with relatively high germination (45-67%), a critical suppression of root length (Min=5 mm, Max=40 mm in arable samples versus Min=40 mm, Max=50 mm in control) and phytomass (0.09-0.19 g versus 0.3 g in control) was observed. These parameters are important for detecting latent phytotoxicity. Radishes also show a significant reduction in root length in arable samples (Min=10 mm, Max=120 mm) compared with the control (Min=1 mm, Max=115 mm). Obtaining such results may be due to the content of phytotoxicants in the soil, which affect the processes of plant growth and development, but do not affect seed germination.

The results obtained substantiate the applicability of the selected bioindicators for monitoring the state of agricultural soils. Agricultural activity in the field under study led to the formation of phytotoxicity of the soil, manifested in the suppression of sensitive cruciferous crops (rapeseed, watercress) and the radish root system. Rapeseed and watercress are highly sensitive bioindicators for monitoring. The revealed heterogeneity of phytotoxicity requires a differentiated approach to assessing soil conditions.

A similar study conducted by Altai State Agrarian University also demonstrates the high effectiveness of the phytoindication method for assessing soil toxicity, which is confirmed by a significant inhibition of the growth of test plants in contaminated samples. The results showed that in the most polluted areas – the Industrial District, school No. 120 – phytotoxicity reached 83% and 64%, respectively, compared with the control. These data are consistent with Marfenina's research, which noted a decrease in the biological activity of soils with heavy metal content above the MPC.

Of particular interest are the revealed differences in the reaction of test cultures. Cruciferous plants (rapeseed, watercress) showed the greatest sensitivity – a decrease in germination to 24% and phytomass to 0.13-0.62 g against control values of 60% and 0.38 g, respectively. At the same time, barley demonstrated relative stability (germination rate 70-100%, phytomass 2.45-3.24 g with control 83% and 3.42 g). This 2-3-fold difference in key indicators confirms the need to use several bioindicators for a comprehensive assessment.

It is important to note that in 45-67% of samples with relatively preserved microgreenage germination, a critical decrease in root length (5-40 mm versus 40-50 mm in the control) and phytomass (0.09-0.19 g versus 0.3 g) was ob-

served. These data, obtained by repeating the experiments 4 times, indicate the presence of latent phytotoxicity, which is not detected by standard methods.

The comparison with the radish data is particularly significant, where the root length in the contaminated samples ranged from 10 to 120 mm versus 1-115 mm in the control. The identified spatial heterogeneity of contamination (the spread of phytotoxicity indicators from 40 to 92% at different sampling points) requires a differentiated monitoring approach. Studies have shown that the use of highly sensitive indicators (rapeseed, watercress) makes it possible to detect contamination at an early stage, when the content of toxicants still does not exceed 1.5-2 MPC.

A comparative analysis of the results of two studies on the assessment of soil phytotoxicity by phytoindication revealed a number of important patterns. Both studies confirmed the high efficiency of this method, demonstrating a significant inhibition of the growth of test plants in contaminated samples - a decrease in indicators by 24-92% relative to the control. At the same time, a pronounced species-specific reaction of plants to pollution was established: cruciferous crops (rapeseed, watercress) showed maximum sensitivity with a decrease in germination to 24% and phytomass to 0.13-0.62 g, while barley showed relative stability while maintaining germination at the level of 70-100%. Of particular value are the identified cases of latent phytotoxicity, when, with relatively high germination (45-67%), a critical suppression of root length (5-40 mm versus 40-50 mm in the control) and phytomass (0.09-0.19 g versus 0.3 g) was observed. The data obtained convincingly prove the need for an integrated approach using several bioindicators and taking into account both germination parameters and morphometric parameters. The revealed spatial heterogeneity of pollution (the range of phytotoxicity indicators from 40 to 92%) underlines the importance of differentiated monitoring of the soil condition. The research results are consistent with each other and confirm the expediency of using highly sensitive indicators (rapeseed, watercress) for early detection of pollution, which is of great practical importance for developing remediation measures for contaminated areas.

Conclusion

The conducted studies have demonstrated the effectiveness of the phytoindication method for assessing the phytotoxicity of soils exposed to agrogenic effects. The results showed a significant inhibition of the growth of test plants in contaminated samples, which resulted in a decrease in key indicators by 24-92% compared with the control. Cruciferous crops (rapeseed and watercress)

showed the greatest sensitivity, with a sharp decrease in germination to 24%, germination energy to 1.0, and phytomass to 0.13-0.62 g. At the same time, barley has demonstrated relative stability, maintaining germination at the level of 70-100%, which confirms the need to use several bioindicators for a comprehensive assessment.

Of particular importance are the identified cases of latent phytotoxicity, when, with preserved germination (45-67%), a critical suppression of root length (5-40 mm versus 40-50 mm in the control) and phytomass (0.09–0.19 g versus 0.3 g) was observed. This underlines the importance of taking into account not only germination parameters, but also morphometric indicators to identify the negative effects of pollutants. The spatial heterogeneity of phytotoxicity (the range of indicators from 40 to 92%) indicates the local nature of pollution and the need for a differentiated approach to monitoring and remediation of soils. The data obtained are consistent with the results of other studies, confirming the expediency of using highly sensitive bioindicators such as rapeseed and watercress for early detection of phytotoxicity.

Thus, the phytoindication method combined with a comprehensive analysis of biometric indicators provides a reliable assessment of soil condition and can be recommended for monitoring agricultural areas. It is advisable to focus further research on the identification of specific pollutants and the development of measures to restore soil fertility.

Conflict of interest information. The authors declare that they have no conflict of interest.

Sponsorship information. The work is published as part of a grant from the federal budget to educational organizations of higher education for the implementation of activities aimed at supporting Student scientific communities.

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ВКЛАД АВТОРОВ

Все авторы сделали эквивалентный вклад в подготовку статьи для публикации.

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Поступила 07.11.2025
После рецензирования 29.11.2025
Принята 10.12.2025

Received 07.11.2025
Revised 29.11.2025
Accepted 10.12.2025