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# *THE EFFECTIVENESS OF BIOMELIORATION TECHNOLOGIES IN THE RESTORATION AND ENHANCEMENT OF DEGRADED SOIL FERTILITY*

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***Abstract.*** *The article considers the current issue of soil degradation and justifies the need to use biomelioration methods as a key tool for restoring their fertility. The research process employed a comprehensive approach, encompassing the analysis of scientific publications and practical examples of the application of biomelioration methods to enhance fertility indicators of degraded soils. The term 'fertility' is defined by three main properties: physical, chemical and biological. The impact of biomelioration methods on restoring fertility is noted, through the accumulation of organic matter, the stimulation of biological activity, and the improvement of soil structure. The primary biomelioration methods and their impact are investigated. Phytoremediation is defined as a process thar aims to reduce toxic elements in contaminated soils, through the cultivation of special plants capable of removing or localising toxic substances in the root zone or above-ground part. The role of organic farming as a method of biomelioration is determined. A scheme of the mechanism of the influence of biomelioration on soil fertility is presented. Recommendations for the implementation of a complex of biomelioration systems for the effective restoration of degraded soils in Ukraine are offered. It is noted that further research should focus on the development of biomelioration systems tailored to specific regions and the evaluation of the long-term economic implications of their implementation.*

***Keywords:*** *soil degradation, soil fertility, biomelioration, green manures, phytomelioration, phytoremediation, microbial preparations, organic farming.*

**Problem Statement.** Soil degradation, caused by intensive anthropogenic loads, climate change and irrational land use, is a global environmental and economic challenge. The loss of humus, deterioration of physical structure, salinisation, acidification and reduction of biological activity of soils results in a decrease in productivity and stability of agroecosystems. Conventional chemical and engineering-based melioration methods frequently incur significant financial costs and can have a deleterious effect on the environment. In this regard, biomelioration – defines as the use of biological factors (including organic fertilisers, plants, microorganisms) to improve soil properties – is gaining strategic importance as an environmentally safe and sustainable approach.

**Review of Recent Research and Publications.** The issue of restoring the fertility of degraded soils using biomelioration methods is constantly being considered in contemporary scientific research both in Ukraine and abroad. In the study by A. Pasenko, O. Sakun, O. Nykyforova, O. Dudnik and M. Kamynina [1], attention is focused on enhancing soil biological activity through agrochemical melioration using unconventional fertilisers. The authors prove that the use of organic fertilisers of natural origin promotes the activation of soil microbiota, improves soil structure, and increases humus content, which collectively form the basis for enhancing soil fertility. In V. Volkohon's work "Biological reclamation of soils: traditional and new" the principles and mechanisms of biomelioration are examined in detail, particularly the role of microorganisms, green manures, and legumes in restoring the biochemical balance of degraded lands. The scholar emphasises that biomelioration measures are both environmentally safe and economically viable within the framework of sustainable land use [2]. The issue of biological methods for remediation of contaminated soils is discussed in the article by V. Samokhvalova, which considers the mechanisms of neutralisation of toxic compounds, in particular heavy metals, using plant and microbiological agents. The author substantiates the effectiveness of biotechnological approaches for soil purification and restoration in area subject to technogenic stress [3].

Foreign sources confirm the trend towards active implementation of biomelioration methods. Thus, the study “Assisted Phytoremediation for Soil Fertility Restoration on Polluted and Degraded Lands” [4], the effectiveness of phytoremediation for improving the fertility of degraded lands is described. The authors note that the synergistic use of plants and microorganisms enables not only the removal of pollutants but also the enhancement of the soil’s physicochemical properties. Similar results are presented in the study “Study of Bioremediation and Soil Fertility: Effect of Vermiremediation on Chlorpyrifos-Contaminated Soil” [5], where researchers proved that the use of earthworms contributes to improving soil structure and restoring its biological activity. The general review “Soil Bioremediation: Technologies and Trends” [6] highlights recent advances in soil purification and restoration technologies, identifying microbiological and phytotechnological remediation as the most promising approaches. In the publication “Degradation of Pesticides: Impact on Soil Fertility and Nutrient Cycling” [7], the mechanisms through which pesticides affect soil fertility are explored, with particular emphasis on the importance of biological processes in stabilising nutrient cycle following the degradation of chemical compounds.

Considerable attention has also been devoted by Ukrainian scholars to the legal aspects of land restoration. In the works of T. Lisova [8] and N. Havrysh, S. Pozniak [9], the current state of regulatory regulation of soil melioration in Ukraine is analysed. The authors emphasise the need to improve the legislative framework in the field of land protection and introduce incentive mechanisms for economic entities implementing environmentally safe biomelioration technologies.

Thus, the analysis of publications indicates that biomelioration methods are considered by scientists as a comprehensive approach to the restoration of degraded soils, combining biological, ecological and legal aspects. The synthesis of accumulated experience demonstrates that their application constitutes a promising direction for ensuring sustainable land use and enhancing the productivity of agroecosystems.

**The aim of the study is** to analyse and systematise data on the influence of biomelioration methods on the key indicators of fertility in degraded soils.

**Materials and Methods.** The research was conducted using an integrated methodological framework combining analytical, field, laboratory, and statistical approaches, enabling a comprehensive assessment of the effectiveness of bioremediation practices on degraded soils. The empirical part of the study covered several types of Ukrainian soils – primarily chernozems, grey forest soils, and light sandy substrates, which represent typical examples of territories exposed to erosion, compaction, depletion of humus, and agrochemical imbalance. For comparative purposes, both conventionally managed and ecologically disturbed plots were examined. Biomelioration interventions included the application of green manure crops, legume-based rotations, microbiological preparations, composted organic matter, and plant-based remediation agents. Each technology was assessed for its contribution to structural improvement, nutrient accumulation, enhancement of biological activity, and restoration of the soil's ecological functions. Field experiments involved systematic sampling at fixed depths following conventional agrochemical protocols.

Laboratory analyses were performed in accordance with national and international standards, including DSTU 4287:2004 for humus assessment, DSTU ISO 14235:2005 for determining active carbon via potassium permanganate oxidation, and DSTU 7863:2015 for nitrogen, phosphorus, and potassium content. Microbiological activity was evaluated by plate-count and substrate-induced respiration methods. Soil pH, bulk density, and aggregate composition were measured using standard soil science procedures to determine the influence of biomeliorants on physical properties.

Statistical processing of data was conducted using the R environment, applying variance analysis, correlation assessment, and reliability testing to verify the significance of observed differences. Spatial differentiation of soil quality indicators and visualization of improvement zones were performed through GIS tools (ArcGIS Pro, QGIS), which enabled the identification of patterns in soil restoration dynamics and supported evidence-based interpretation of biomeliorative efficiency.

**Results and Discussion.** The problem of soil degradation is one of the most pressing environmental threats of the present time. Soil degradation is considered as a partial or complete disruption of the functions of the soil ecosystem. The complex interaction between natural factors (e.g. soil, climate, vegetation cover, topography) and anthropogenic processes (e.g. urbanisation, land use, overgrazing, military operations) is associated with soil degradation. The European Union has recognised ten threats to soil functions: water and wind erosion; reduction of organic matter; pollution; soil crust formation; compaction; loss of soil biodiversity; salinisation; floods and landslides; desertification; acidification. The most common types of degradation are soil erosion (about 13% of Europe's arable land experiences unsustainable soil loss (>5 t ha per year), compaction (about 36% of European soils are affected), salinisation (about 3 million ha of European soils), pollution (there are about 2.5 million potentially contaminated sites in Europe, about 14% of which (340,000 sites) are contaminated and require remediation measures) [4].

Another type is physical pollution, which involves changes in the physical properties of soils, such as excessive compaction. There is also chemical pollution, which occurs due to the ingress of toxic substances, heavy metals and explosive combustion products, which leads to soil poisoning. Finally, biological degradation occurs, manifested in the mass mortality of living organisms, particularly microorganisms, which play a crucial role for soil fertility [10]. The most common biomelioration methods include: sideration (use of green fertilisers); use of legumes; microbiological melioration; phytomelioration; organic farming (Table 1).

Table 1

Main biomelioration methods and their effects on soil properties

| Biomelioration method | Core principle | Effect on soil | Result of application |
|---|---|---|---|
| Sideration (use of green fertilisers) | Cultivation of plants (mustard, lupin, rye, phacelia) with subsequent plowing. | Increases organic matter content, improves structure. | Increase in humus content by 0.1–0.2% in 2–3 years. |
| Legumes | Symbiosis with *Rhizobium* bacteria for nitrogen fixation. | Enriches soil with biological nitrogen. | Increase in nitrogen balance by 40–60 kg/ha. |
| Microbiological melioration | Application of microorganisms (mycorrhizae, | Activates soil microflora and mobilises nutrients. | Increase in crop yield by 10–15%. |

| | | | |
|---|---|---|---|
| | rhizobacteria, phosphate-mobilising bacteria). | | |
| Phytomelioration | Use of special plants for the reclamation of degraded lands. | Fixes slopes, reduces erosion, improves structure. | Reduction of soil erosion losses by 30–40%. |
| Organic farming | Use of composts, manure, and mulch. | Increases organic matter content, improves water permeability. | Stabilisation of fertility, reduction of soil compaction. |

*Compiled by the authors based on [4, 10]*

Biomelioration methods act comprehensively, altering both the chemical and biological properties of the soil. The organic matter of green manure crops and post-harvest residues decomposes through microbial activity, forming humus substances. This process improves soil buffering capacity and fertility, leading to an increase in humus content. According to the Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky, the incorporation of green manure in crop rotation contributes to an increase in the humus content by 0.1–0.2% in 2–3 years. Green manures not only retain key nutrients (nitrogen, phosphorus, potassium) in organic form, preventing their leaching and nitrate pollution of groundwater. They are also a powerful source of nitrogen: green mass adds approximately 200-250 kg/ha to the soil, which replaces 600-700 kg/ha of traditional nitrogen fertilisers. In general, the use of post-harvest green manures together with by-products and root residues fully compensates for the removal of organic matter. This provides an additional input of 68.4 centners of organic matter per hectare, which is equivalent to 1620 tons of manure [11].

An essential aspect of soil restoration is the stimulation of microbiological activity. Biomelioration promotes the development of beneficial microflora involved in the mineralisation of organic compounds and the nutrient cycling process. Microorganisms, such as fungi and bacteria, secrete polysaccharides and other biopolymers that act as a biological “adhesive”, binding fine soil particles into stable aggregates. This process is crucial for restoring soil structure, improving porosity, aeration, and water permeability, thereby preventing erosion and the formation of soil crusts. Microbiological melioration significantly increases the availability of nutrients.

Nitrogen-fixing bacteria (e.g., *Rhizobium* species) convert atmospheric nitrogen ($N_2$) into forms available to plants, and phosphate-mobilising microorganisms dissolve insoluble mineral compounds of phosphorus and potassium, making these nutrients accessible for plant uptake. The highest level of crop rotation productivity on sod-podzolic soils in terms of feed units was achieved under the organic-mineral fertilisation system (green manure + manure + NPK), which exceeded the productivity of rotations under on the traditional NRK + manure system by 21% without inoculation and by 26% on a background with inoculation [12].

Microflora also plays a key role in humus formation, decomposing organic residues and synthesising stable humic substances, which constitute the foundation of long-term fertility. Moreover, microbiological processes contribute to soil detoxification, as certain groups of bacteria can degrade chemical pollutants (bioremediation), such as pesticides and petroleum products, while antagonistic microorganisms help suppress soil pathogens. This is particularly important for the restoration of soils degraded because of military activities. A study [10] demonstrated that the application of nitrogen-phosphorus mineral fertiliser, straw, and the biological preparation "Ecostern Detox" as ameliorants had a positive effect on the agrochemical indicators of the soil affected by warfare in the Kharkiv region, optimising microbiological processes, although no systemic impact on the dynamics of mobile heavy metal content was detected. The beneficial influence of the amelioration measures on the soil environment was validated through biotesting: the synergistic action of the applied factors resulted in an increase in maize plant height by 14.3–18.1%, above-ground mass by 24–46.2%, and root mass by 13.3–14.3%. Research conducted at the Uman National University of Horticulture established that the use of microbial preparations such as Ryzobofit and Phosphoenterin increases cereal crop yield by 10–15%, while the phosphorus utilisation rose by 25%.

The improvement of soil structure is achieved through the root system of green manures, which loosen the soil, improving its aeration and water permeability. According to the research of the National Scientific Centre “Institute of Agriculture NAAS” conducted on irrigated plots, the potential of green manure crops to increase soil fertility is directly dependent on the amount of biomass they produce. The amount of accumulated biomass is a function of the combined action of two factors: a favourable hydrothermal regime of the growing season and correctly selected agrotechnical measures. At the same time, disk tillage demonstrated higher efficiency for the accumulation of green manure mass than the use of zero technology (No-Till). In particular, the following volumes of green manure mass were recorded during disk tillage: 11.97 t/ha (buckwheat), 10.13 t/ha (annual white sweet clover) and 14.47 t/ha (phacelia tanacetifolia). Zero technology provided slightly lower indicators: 10.74 t/ha, 9.38 t/ha and 13.25 t/ha respectively [13]. Thus, soil cultivation stimulates more intensive processes of organic matter transformation, while slowing down its mineralisation. This means that the cultivated soil loses less organic matter, and the speed of the biological cycle of substances and energy in it increases. A key feature of cultural soil formation is an increase in soil biogenicity against the background of a decrease in the intensity of decomposition of organic residues, which indicates deep genetic changes in the method of organic matter transformation [1].

Biomelioration methods represent one of the most important and most effective groups of measures in combating soil erosion, as they use plant cover to protect, strengthen and restore soil fertility. These methods are aimed at creating a stable biological barrier that prevents the destructive effects of water and wind. Biomelioration operates through several key directions that provide comprehensive protection against erosion. Firstly, the physical stabilisation of the soil by the root system of plants prevents it from being washed away (water erosion) or blown off (wind erosion). Secondly, the above-ground part of plants (leaves, stems, cover crops) absorbs the energy of raindrops, preventing them from destroying the soil structure and forming a surface crust. Thirdly, plant cover and crop residues reduce the velocity of surface water runoff, allowing more time for infiltration (absorption) and significantly diminishing its destructive power. Fourthly, root secretions and decomposition of organic residues contribute to soil aggregation (formation of strong lumps), which increases its water permeability and resistance to destruction. The most common and effective biomelioration measures are:

- afforestation is the creation of protective forest plantations (forest belts, field buffer strips, border plantations) on agricultural lands;

- soil-protective crop rotations are a scientifically substantiated alternation of crops in time and on the territory, which includes perennial grasses and other ground cover plants;

- grassing and turfing involves the creation of a permanent grass cover on the most erosion-prone areas (steep slopes, along the banks of reservoirs, at the bottom of gullies), where soil cultivation is prohibited or impractical;

- the use of cover crops and mulching. Cover crops (green manures) are plants that are sown in the gaps between the main crops or after harvesting. They cover the soil during periods when it usually remains bare, protecting it from rain and wind. Mulching with organic residues is the leaving of crop residues (straw, stubble) on the soil surface (for example, with No-Till or Mini-Till technologies). Mulch prevents direct contact of rain with the soil, reduces moisture evaporation and slows down runoff. In steppe regions, phytomelioration using perennial grasses (safflower, fescue) has been shown to reduce soil erosion losses by 30–40%.

It should be noted that legumes provide plants with biological nitrogen, and some types of microorganisms with available phosphorus and potassium, which optimises the nutrient regime of soils. According to research, each hectare of lupine can accumulate 40-50 tonnes of organic matter, which is a valuable source of organic carbon and biological nitrogen. In addition to lupine, other legumes, such as field pea, sweet clover, and vetch, are widely used in the humid zone of the Polissia region. When these legume green manures are plowed into the soil together with straw and barley root residues, they provide a significant increase in the content of nutrients: nitrogen by a factor of four times, phosphorus by 2.8 times, and potassium by 2.5 times. Since green manures contain a small amount of lignin and aromatic compounds (those that participate in the formation of humus), they are quickly mineralised. This guarantees a prompt supply of carbon to feed soil microorganisms. The main criteria for selecting green manures for catch crops are their yield, duration of the growing season, phytosanitary properties, and seed reproduction coefficients [11].

An important direction of phytomelioration is phytoremediation – the purification of soils from toxic pollutants using plants. The mechanisms of phytoremediation include phytoextraction, degradation, filtration, accumulation, stabilisation and evaporation. Extraction, transformation and sequestration effectively remove pollutants such as heavy metals and radionuclides. In this case, hyperaccumulator plants play an important role, which can grow on soils rich in heavy metals, absorbing a large amount of these metals during the growing season and not showing any signs of phytotoxicity [6]. For the purification of soils contaminated because of military aggression, the most promising crops are pea (Pisum sativum L.) and miscanthus (Miscanthus giganteus), since they demonstrate the widest range of absorption of toxic substances. When choosing a specific crop for phytoremediation, an important issue is the feasibility of further use of its biomass. In this context, energy crops used to produce pellets or briquettes are a better choice. Castor oil (Ricinus communis L.) can be processed into bioethanol, which solves the safety problem, since its contaminated biomass does not enter the food chain. Energy crops, such as miscanthus (Miscanthus giganteus), not only contribute to phytoremediation, but also increase the energy stability of the country, reducing dependence on fossil fuels and developing renewable energy sources. In addition, the choice of crop for soil purification should consider the climatic characteristics of the region. For instance, sorghum (Sorghum bicolor (L.) Moench) is appropriate for use in southern Ukraine due to its biological resistance to high temperatures [13].

International experience in rational land use indicates an extremely high potential for implementing organic farming methods. Biological farming, also called organic farming, involves the rejection of chemicals inputs not only for crop production products, but also for soil fertility restoration. This type of farming significantly reduces the use of external factors of production and resources by limiting the use of chemically synthesised fertilisers and pesticides and making extensive use of natural factors. Composting is an effective direction of the bioremediation for soils contaminated with pesticides. This environmentally friendly method of biostimulation consists in the microbial decomposition of organic matter under oxidative conditions to obtain a stable organic fertiliser. Due to the thermophilic temperatures that occur during the process, the introduction of compost increases and accelerates the biodegradation of pesticides. The main destructors of pollutants are actinomycetes, fungi, and nitrifying bacteria, which are both drivers of reclamation and indicators of soil quality [14]. Therefore, biomelioration methods comprehensively, transforming both the chemical and biological properties of the soil, creating conditions for enhanced fertility and sustainability of agroecosystems (Figure 1).

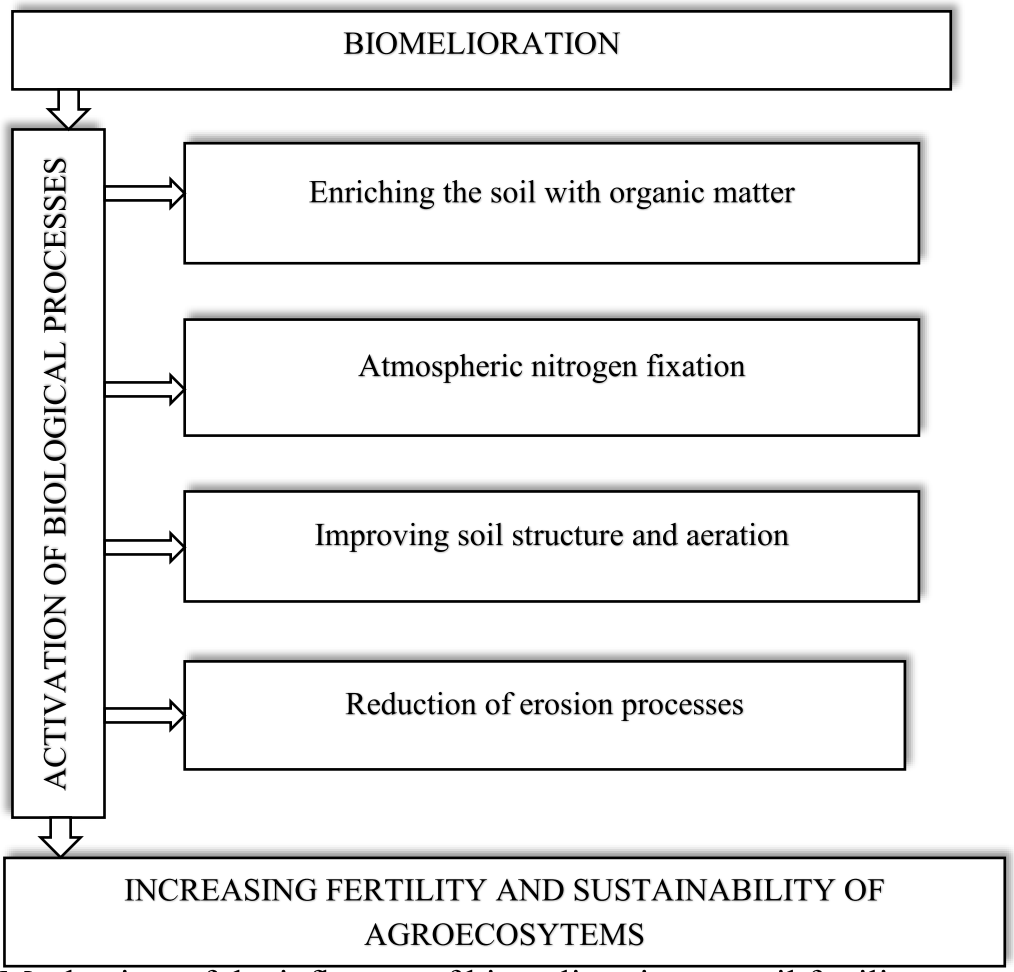


Figure 1. Mechanism of the influence of biomelioration on soil fertility

*Compiled by the authors*

For the effective restoration of degraded soils in Ukraine, it is necessary to implement complex biomelioration systems that include the following measures:

- introduction of soil-protective crop rotations, with the mandatory inclusion of perennial grasses and legumes to increase the humus content;
- active use of green manures (buckwheat, phacelia, sweet clover) to compensate for the loss of organic matter and provide the soil with nitrogen;
- application of phytoremediation to clean soils from toxic pollutants, using crops with a wide absorption range and energy crops, whose biomass can be processed into bioethanol or pellets, which guarantees the avoidance of its entry into the food chain;
- selection of crops based on the climatic features of the region;
- stimulation of microbiota using microbial preparations and composting, which accelerates pesticides decomposition and enhances nutrient availability for plants;
- at the state level, it is necessary to improve the legislative framework in the field of land protection and introduce incentive mechanisms for business entities that implement environmentally safe biomelioration technologies.

**Conclusions and Recommendations.** Biomelioration represents an important, environmentally safe and economically viable approach to the restoration of degraded soils. It is considered as a comprehensive method that integrates biological, ecological and legal dimensions. Its application constitutes a promising direction for ensuring sustainable land use and increasing the productivity of agroecosystems. Biomelioration methods combine natural restoration processes with modern scientific approaches, thereby ensuring long-term preservation of soil potential. Under the conditions of Ukraine, biomelioration should become one of the priority areas of greening agriculture, as it provides a balance between productivity, environmental safety, and economic efficiency. Further research should focus on the development of regionally adapted biomelioration systems and the assessment of their long-term economic effectiveness.

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***О. П. Панасюк, В. С. Костюк***

***ЕФЕКТИВНІСТЬ БІОМЕЛІОРАЦІЙНИХ ТЕХНОЛОГІЙ У ВІДНОВЛЕННІ ТА ПІДВИЩЕННІ РОДЮЧОСТІ ДЕГРАДОВАНИХ ҐРУНТІВ***

***Анотація.*** *У статті розглянуто актуальну проблему деградації ґрунтів та обґрунтовано необхідність застосування біомеліораційних методів як ключового інструменту для відновлення їхньої родючості. Метою статті є аналіз та систематизація даних впливу біомеліораційних методів на основі показників родючості деградованих ґрунтів. У процесі дослідження використано комплексний підхід, що передбачає аналіз наукових публікацій, а також практичних прикладів застосування методів біомеліорації для підвищення показників родючості деградованих ґрунтів. Родючість визначається як сукупність трьох основних властивостей, а саме фізичних, хімічних та біологічних. Відзначено вплив біомеліораційних методів на відновлення родючості через накопичення органічної речовини, стимуляцію біологічної активності, покращення структури ґрунту. Досліджено основні біомеліораційні методи та їхній вплив. Розглянуто фіторемедіацію як захід, який направлений на зменшення токсичних елементів у забруднених ґрунтах, завдяки вирощуванню спеціальних рослин, здатних виводити або локалізувати токсичні речовини в кореневій зоні або надземній частині. Визначено роль органічного землеробства як методу біомеліорації. Представлено схему механізму впливу біомеліорації на родючість ґрунтів та рекомендації з впровадження комплексу біомеліораційних систем, для ефективного відновлення деградованих ґрунтів в Україні. Зазначено, що подальші дослідження мають бути спрямовані на розробку регіонально адаптованих біомеліораційних систем та оцінку довгострокового економічного ефекту від їхнього впровадження.*

***Ключові слова:*** *деградація ґрунтів, родючість ґрунту, біомеліорація, сидерати, фітомеліорація, фіторемедіація, мікробні препарати, органічне землеробство.*