

PROMISING CYANOBACTERIAL SPECIES RECOMMENDED AS BIOFERTILIZERS FOR AGRICULTURAL SOILS

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Aim. To identify the criteria and select cyanobacterial species that may be used as biofertilizers for agricultural soils. **Methods.** Specific methods of synthesis, logical analysis, and correlation of scientific results, comparison, systematization, explanation, and deduction were used in the work. Field studies were conducted on chernozem (typical, common, and leached) under various crops (sunflower, wheat, barley, corn, rape, and pea) in the central and southern regions of the Republic of Moldova from 2010 to 2025. **Results of studies.** The criteria for selecting bacteria to be applied as biofertilizers on agricultural lands, used for the cultivation of crop plants, were established as follows: dominance, spreading, high tolerance to environmental factors (without intermediate accommodation stages), a short generation time, and potential for industrial cultivation. The cyanobacteria recommended as biofertilizers for agricultural soils were identified, and their taxonomic position, from genus to species, was presented. The most representative genera of cyanobacteria recommended as biofertilizers for various soil types are as follows: *Microcystis*, *Nostoc*, *Anabaena*, *Cylindrospermum*, *Tolypothrix*, *Calothrix*, *Oscillatoria*, *Phormidium*, *Lyngbya*, *Schizothrix*, and *Microcoleus*. Also, 65 species of cyanobacteria, representatives of the dominant and globally widespread genera, recommended for use as biofertilizers, were determined. The optimal dose of cyanobacterial fertilizers (ranging from 5 to 258 kg/ha) and the form of their administration to ensure the sustainability of the health of soils and crops were established. **Conclusions.** Cyanobacteria are promising biofertilizers with proven impact on soil health and crop productivity. The study defines the criteria for selecting effective species and highlights the recommended genera and species for various soil types. Their application in the living form may support the fertility and sustainability of agroecosystems.

Keywords: cyanobacteria, biofertilizers, soils.

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SOIL CYANOBACTERIA AND THEIR CONTRIBUTION TO SOIL FERTILITY AND SUSTAINABILITY

Soil cyanobacteria are organisms that constitute a part of natural soil biota and play a relevant role in maintaining the ecological balance of soils. In most cases, the involvement of soils in intensive agricul-

tural production leads to a quantitative and qualitative imbalance in soil algae, in general, and cyanobacteria, in particular, which results in ecological instability of the soil ecosystem and may even lead to the modification of its functions. The environmental value of soil algae and cyanobacteria includes their crucial role in initial production, release of biochemical stimulants

and plant growth promoters in soil, nitrogen fixation, mineral solubilization, improvement, and maintenance of soil fertility (Joseph et al., 2024). In addition, some allelopathic compounds, produced by microalgae/cyanobacteria, may serve as ecological herbicides or biocontrol agents. A relevant aspect of cultivating terrestrial plants is the solubilization of mobile phosphate forms in soil, which may be done by cyanobacteria. The ability for solubilization changes depending on their systematic position, even on strain specificity. Recent studies highlighted that the most efficient species of cyanobacteria, mobilizing phosphorus, belong to the genera *Anabaena*, *Calothrix*, *Nostoc*, and *Scytonema*. The studies, conducted using 28 cyanobacterial species, demonstrated that only two strains from the genus *Nostoc* sp. had considerable bioactivity from the standpoint of phosphate solubilization (Toribio et al. 2020). In addition, a recent study compared the possibilities of phosphorus solubilization by *Anabaena* sp. with a commercially available product, based on the bacterial consortium, consisting of *Citrobacter freundii*, *Enterobacter cloacae*, *Pseudomonas putida*, and *Comamonas testosteroni* (Afkairin et al. 2021). The results demonstrated that *Anabaena* sp. had higher phosphorus solubilization than the product of the bacterial consortium.

In addition to the aforementioned, the algalization of soils with cyanobacterial fertilizers is a sustainable solution for restoring edaphic algaeflora biodiversity. Due to their properties, cyanobacteria can be used as biofertilizers in both living and dry states, with consideration given to their rapid activation under optimal development conditions. However, the application of a living cyanobacterial biomass as fertilizers is more effective and promotes faster accommodation and development of cyanobacterial populations, enhancing the effectiveness and impact of fertilizers. The application of cyanobacterial fertilizers is known to promote soil decontamination, maintain humidity, enhance resistance to global environmental changes, decrease erosion (due to better soil structurization), and increase the number and quality of bacteria, especially nitrogen-fixing ones, and some fungi. It is noteworthy that compaction with cyanobacterial fertilizers (except for cases of excessive application) cannot replace mineral or organic fertilization (for instance, compost) but may be viewed only as an additional source of streamlining the effects of these fertilizers, accelerating the development of relevant soil biota representatives, and increasing the performance of cultivated crops.

Positive effects of applying cyanobacterial fertilizers in crop cultivation. The interest in the application of cyanobacterial fertilizers is explained by their positive effect on cultivated crops. The application of the cyanobacterium *Oscillatoria annae* during the cultivation of *Aloe barbadensis* Mill. resulted in the increase in the fresh weight of leaves from 22 g to 124.30 g, and the application of cyanobacteria *Nostoc* sp., *Anabaena* sp., *Tolypothrix* sp., *Leptolyngbya* sp., and *Synechocystis* sp. during the cultivation of *Ocimum basilicum* L. led to the increase in the height of plants ($\leq 32\%$), the number of leaves ($\leq 24\%$), and fresh weight of leaves ($\leq 26\%$) (Moorthy, K., & P, M., 2012; Santini et al., 2022).

While cultivating cucumbers in hothouse conditions, the application of cyanobacteria *Nostoc flagelliforme*, *N. gelatinosum*, *Cylindrospermum licheniforme*, *Anabaena variabilis*, *A. propinqua*, and *Anabaenopsis* sp. stimulated the growth in height (by 30.5–46.46%), the number of inflorescences (by 12.3–44.44%), and the number of fruit (by 27.04%). (Dobrojan et al., 2014). The application of *Cylindrospermum licheniforme* and *Anabaena variabilis* biomass during tomato cultivation stimulated stem height growth, increased the number of tomatoes per plant (1.3–1.62 times), and tomato productivity (1.31–1.37 times) (Dobrojan et al., 2017). Numerous studies confirm the beneficial effects of cyanobacterial fertilizers on wheat, barley, sunflower, rape, rice, peas, corn, and other crops (Dobrojan et al., 2019; Dobrojan et al., 2019; Kollmen et al., 2022). These results confirm the potential of cyanobacterial fertilizers to stimulate plant growth and productivity, highlighting the importance of correct species selection and application for different crops.

Methods. Specific methods of synthesis, logical analysis, and correlation of scientific results, comparison, systematization, explanation, and deduction were used in this study. Field studies were conducted by the authors on different subtypes of chernozem (typical, common, leached) under various crops (sunflower, wheat, barley, corn, rape, pea) in the central and southern regions of the Republic of Moldova in 2010–2025.

RESULTS OF STUDIES AND THEIR DISCUSSION

Principles of selecting cyanobacterial biofertilizers. The main problem in applying cyanobacterial fertilizers, which requires a very meticulous initial

approach, is selecting species to be applied as biofertilizers, considering that populations of soil algae and cyanobacteria (formerly called “blue-green algae”) follow the fundamental laws of phytocenoses. In addition, while selecting cyanobacterial fertilizers for soils under intensive agricultural use, it is crucial to consider, first of all, such indicators as dominance, species or group distribution, species-specific characteristics, and other phytocenotic indicators relevant to agroecosystems, as well as the geographic distribution and specific resistance to environmental factors. The incorrect selection of cyanobacterial species used as biofertilizers may provide short-term beneficial effects, but in the long run, it can lead to structural and functional changes in the algal-cyanobacterial biota, which can degrade the ecosystem status of the soil. Moreover, allochthonous cyanobacterial species introduced through soil algalization may create competition and antagonistic relationships with the native cyanobacterial-algal biota, potentially reducing or even eliminating beneficial effects on both the soil and cultivated plants.

In addition, the selection of cyanobacterial species must consider physiological traits, particularly their ability to resist drought, temperature fluctuations, and strong insolation, as well as the capacity for easy and rapid transition between vegetative and dormant stages without intermediate accommodation stages. Cyanobacterial species should also possess a short regeneration capacity, ideally ranging from 8–12 hours

up to a few days, an accelerated life cycle, rapid reproduction, and the ability to redistribute within the lower soil layers while proliferating abundantly at the surface. An important criterion is the fact that selected cyanobacteria exhibit high tolerance to environmental factors (temperature, light, precipitation), are easily cultured, grow rapidly, and are suitable for industrial-scale cultivation.

It is noteworthy that the most advantageous species as promising biofertilizers are heterocystous phototrophic soil cyanobacteria, which have minimal cell volumes, maximal specific surface area, maximal specific growth rates, minimal generation time, and consequently the highest biotic potential. Filamentous cyanobacteria are also preferred, as they can achieve much higher population numbers than unicellular algae and provide potential for nutrient cycling dynamics in the soil.

The application of edaphic cyanobacterial fertilizers is recommended to be perennial, considering that approximately 10–30% of the total applied biomass remains by the end of the crop vegetation period, and after plowing or other soil processing methods, a significant portion of the biomass reaches the lower soil layers. This process is favorable for the subsequent “soil bloom” phenomenon, usually resulting from the migration of phototrophic cyanobacteria from lower soil layers to the upper ones. In case of perennial application, it is very likely that the soil will contain a sufficient amount of cyanobacterial cells,

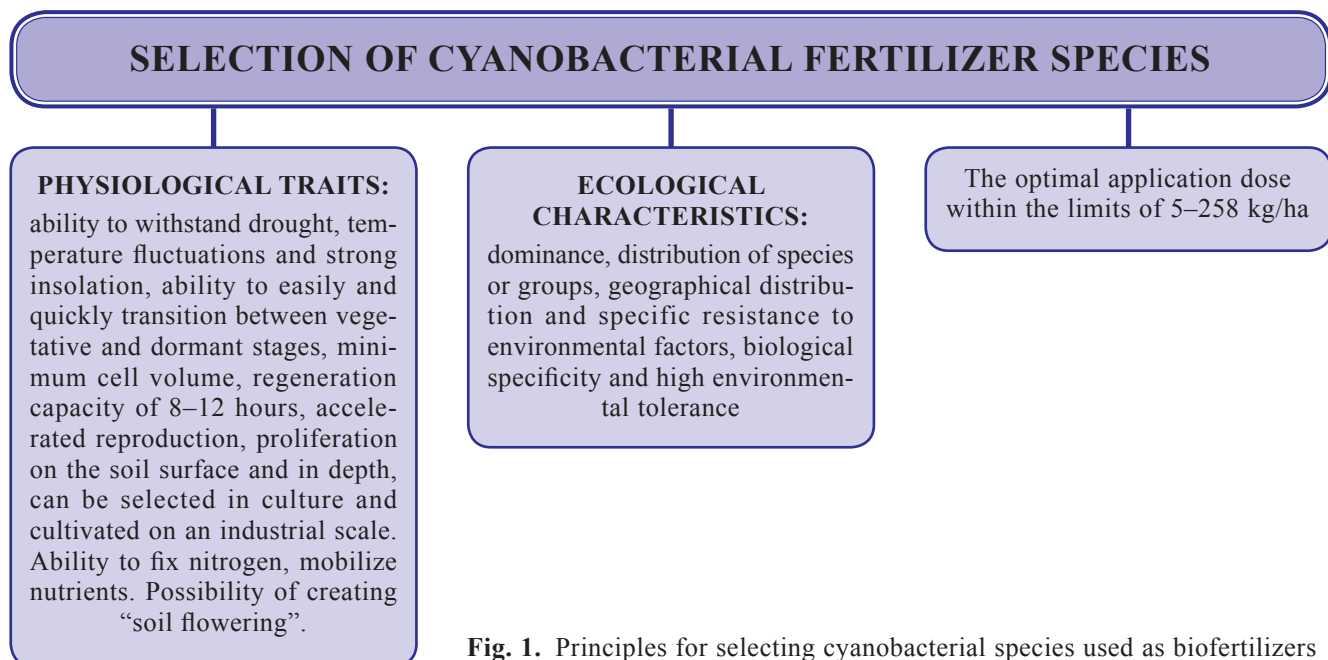


Fig. 1. Principles for selecting cyanobacterial species used as biofertilizers

both in number and distribution, to ensure uniform “soil bloom,” leading to consistent proliferation of cyanobacteria and algae across the entire surface and resulting in beneficial effects.

It is also essential to consider the dose of applying cyanobacterial fertilizers, as low doses may fail to produce effects, while excessively high doses may cause adverse outcomes. Another critical factor in selecting cyanobacterial fertilizers is the biological specificity and environmental tolerance of the species. It is well known that most active soil cyanobacteria are moisture-dependent; thus, increased soil humidity enhances biomass growth and their effects on soil and plants, and vice versa. The prerequisites for rapid reactivation of biological nitrogen fixation and photosynthetic activity in cyanobacteria were demonstrated by E. Pancratova, who noted that these organisms can resume photosynthesis and nitrogen fixation within 30 minutes after rehydration (Pancratova, 1965).

Global spreading of soil cyanobacteria. To isolate a general law regarding the cyanobacterial species recommended for algalization of soils, used to cultivate crops, we proposed to analyze the specific systematics of cyanobacteria from soils involved in agriculture and used for other purposes, from different regions of the world, highlighting the most abundant, predominant, and widespread species. This criterion is the basic indicator, which is in line with natural laws and should be used as a basis for selecting cyanobacterial biofertilizers.

Considering that the application of cyanobacterial fertilizers is envisioned in crop cultivation, it is essential to examine the systematics of the algal flora and soil cyanobacteria specific to these ecosystems. The first phytocenotic analyses of the soil algal formations specific to cultivated lands highlighted that cyanobacteria develop intensively on these soils (Allison et al., 1937; Esmarch et al., 1911; Petersen et al., 1935). The exceptions to this rule are soils used for tea, mandarin, and lavender cultivation, soils with an excess of acid superphosphate, and ploughed soils in the first stage of development, such as light brown soils. The study conducted by Golerbah M.M. and Shtina E.A. highlighted the fact that on cultivated soils, cyanobacteria, especially those of the genera *Nostoc* and *Anabaena*, had specific intense development (Golerbach et al., 1969).

It leads us to the understanding that these are the most important species with the potential to be used as biofertilizers. Other research indicates that the

cyanobacteria *Nostoc punctiforme*, *Anabaena cylindrica*, *A. sphaerica*, and, in particular, species of the genus *Cylindrospermum* predominate on arable soil (Perminova, 1964). In particular, it is highlighted that cyanobacteria predominate on cultivated soils and that the ratio between the genera *Nostocales* and *Oscillatoriales* is 3:1, 2:1, and 1.5:1, with the predominance of the species *N. punctiforme*, *Anabaena cylindrica*, *A. sphaerica*, and species of the genus *Cylindrospermum* (Perminova, 1964). From the genus *Cylindrospermum*, the species *Cylindrospermum licheniforme* shows intensive development in the soil in India and other regions. According to the research carried out by Metting B., the diversity of soil cyanobacteria is presented in approximately 38 genera (Metting, 1981). At the same time, according to research conducted by Prof. Victor Şalaru, cyanobacteria predominate in cultivated soils in the Republic of Moldova, with a preponderance of the following species: *Nostoc linckia*, *N. punctiforme*, *N. microscopicum*, *Anabaena variabilis*, *Cylindrospermum licheniforme*, and several species of the genus *Phormidium*, etc. (Şalaru, 1996).

These cyanobacterial species are mainly common in the soils of Romania, Hungary, Moldova, and Ukraine. Therefore, their application is reasonable and promising for all soil types of the entire Danubian region.

Recent research on cyanobacteria in soils used in the cultivation of vineyards and orchards in the southern region of the Republic of Moldova has highlighted the fact that the most abundant development was demonstrated by the following species: *Nostoc pruniforme*, *Anabaena variabilis*, *Oscillatoria brevis*, *Phormidium ambiguum*, *Phormidium tenue*, *Nostoc commune f. sphaericum*, *Gloeocapsa magma*, *Phormidium terebriforme*, *Oscillatoria chalybea* (Ciobanu, 2022).

It should also be taken into consideration that in the soils, used for crop cultivation, green algae predominate, which is of great interest for biofertilization, but the primary role is played by cyanobacteria, especially the species of *Plectonema*, *Cylindrospermum*, and *Nostoc*. The spectrum of cyanobacteria also changes depending on the cultivated crops. Thus, intensive development of the species of *Lyngbya*, *Plectonema*, and *Phormidium* is noted in the fields with winter crops, and after the application of mineral fertilizers, *Anabaena*, *Cylindrospermum*, *Phormidium*, and *Lyngbya* also develop intensively. In soils, used for

perennial crop cultivation, the groups of cyanobacteria *Nostoc-Anabaena*, *Nostoc*, and small quantities of *Cylindrospermum* and species of *Phormidium* and *Plectonema predominate* (Golerbah, 1969).

Cyanobacteria are also pioneers of soils, strongly affected by erosion. Our study of the edaphic algal flora of cultivated and erosion-affected soils demonstrated that some cyanobacterial species from the genera *Cylindrospermum*, *Phormidium*, *Microcoleus* also have anti-erosion properties (bring structure to soils) and can be used as biofertilizers.

Soil cyanobacteria in the Siberian region cover approximately 109 species, belonging to 2 classes, 3 orders, 10 families, and 28 genera. Species from the orders *Oscillatoriales* (59 species), *Chlorococcales* (31 species), and *Nostocales* (30 species) predominate. The most common species, especially in the mineral water region, are *Nostoc punctiforme*, *Leptolyngbya foveolarum*, *L. boryana*, and *Phormidium ambiguum* (Dobovic, 1998; Maximova et al., 2004).

On the soils of the northwestern region of the East European Plain, the most dominant cyanobacteria are those from the families *Nostocaceae*, *Merismopediaceae*, *Phormidiaceae*, *Pseudanabaenaceae*, especially representatives of the genera *Anabaena*, *Phormidium* and *Nostoc* (Davidov, 2006).

Another important indicator in selecting cyanobacterial biofertilizers is the diversity of cyanobacteria in the crusts that generate the phenomenon of “soil bloom”. Thus, the study conducted in the southeastern part of the Eastern European plain highlights the fact that in poly-species soil communities, the dominant species are those from the genera *Nostoc*, *Cylindrospermum*, *Scytonema*, *Microcoleus*, *Phormidium*, *Chlorhormidium* (Domracheva, 1998). The analysis of cyanobacteria, forming the soil crusts, demonstrated that the most common species belonged to the genera *Nostoc*, *Coccomyxa*, *Chlamydomonas*, *Leptolyngbya*, *Stenomitos*, *Pycnacronema*, *Stigonema*, and *Eunotia* (Patova, 2023).

The study on the flora of algae and soil cyanobacteria was also carried out in Egypt. Out of the 218 species of algae identified, cyanobacteria constituted 143 species, or 65.35% of the entire algal population, and the most predominant species belonged to the genera *Oscillatoria*, *Phormidium*, *Lyngbya*, and *Nostoc* (Osman et al., 2003).

Other systematic research carried out in agricultural soils in the city of Al Diwaniyah in Iraq re-

vealed that out of the 26 species of cyanobacteria, the most dominant ones were *Oscillatoria* sp. with a percentage of 50%, followed by *Phormidium* sp. 19.230%, then *Chroococcus* sp., *Spirulina* sp. 7.692% and *Gloeocapsa* sp., *Microcoleus* sp., and *Schizothrix* sp., which reached up to 3.864%. The species *Oscillatoria acuta*, *O. laetevirens*, *O. tenuis*, *Phormidium anomala*, and *P. pachydermiticum* were detected in all the investigated soils (Alghanmi, 2018).

The floristic analysis of cyanobacteria specific to agricultural soils in Uzbekistan has highlighted that, depending on the cultivation technology, the following species of cyanobacteria generally predominated in the region: *Phormidium jadinianum*, *Cylindrospermum stagnale*, *Calothrix gracilis*, *Phormidium fragile*, *Phormidium incinatum*, *Cylindrospermum michailovskoense*, *Calothrix elenkinii*, *Tolypothrix tenuis*, *Oscillatoria brevis*, *Oscillatoria splendida*, and *Phormidium braunii* (Abdujaborovna, 2024). The diversity of dominant soil cyanobacteria in the Taiwan region demonstrated that the most common cyanobacterial species found in the studied agricultural lands were from the genera *Anabaena*, *Calothrix*, *Lyngbya*, *Microcoleus*, *Nostoc*, *Oscillatoria*, and *Phormidium* (Lin Ch.-Su., 2013). These species are cosmopolitan and are found in scientific literature (Song et al., 2005; Begum et al., 2008; Khaybullina et al., 2010).

In desert soils, the most dominant and abundant species of cyanobacteria are from the genera *Microcoleus*, *Scytonema*, *Phormidium*, *Trichocoleus*, *Leptolyngbya*, *Nostoc*, *Anabaena*, and *Tychonema* (Hagemann et al., 2015; Zhang et al., 2005a; Etemadi-Khah et al., 2017; Felde et al., 2019; Zhang et al., 2021; Sosa-Quintero et al., 2022; Cameron, 1962).

The main genera of cyanobacteria in the Brazilian tropical savanna (Cerrado) include *Microcoleus*, *Nostoc*, *Leptolyngbya*, *Porphyrosiphon*, and *Pycnacronema* (Machado de Lima et al., 2019; Machado de Lima et al., 2021; Venkataraman, 1981).

In the cold polar region, species from the families *Chroococcales*, *Pseudanabaenales*, and *Oscillatoriales predominate* (Pushkareva et al., 2016; Pushkareva et al., 2018; Pushkareva et al., 2015).

In the areas of karst desertification, 200 species of soil cyanobacteria were identified, with the predominance of filamentous ones — 77.4% of the total number of cyanobacteria. The dominant genera were *Scytonema*, *Oscillatoria*, *Lyngbya*, *Nostoc*, and *Gleo-*

capsa, with filamentous cyanobacteria being overwhelmingly dominant (Chen et al., 2023). Research conducted on sandy soils with the administration of cyanobacterial fertilizers, the species *Microcoleus vaginatus*, *Scytonema javanicum*, and *Phormidium tenue*, showed that their application improved and stabilized soils (Xu et al., 2010; Zheng et al., 2011; Zheng et al., 2013; Liu et al., 2013).

Another critical indicator in the selection of cyanobacteria used as biofertilizers in the context of climate aridification is the floristic analysis of dominant species in arid territories. Thus, the species *Scytonema hyalinum* and *Tolypothrix distorta* have been reported to be essential components of the soil biota in many nutrient-poor arid soils worldwide and are of interest for the algalization of these soils (Garcia-Pichel et al., 2001; Yeager et al., 2007; Flechtner et al., 2008; Dojani et al., 2014). Research on the algalation of degraded dry soils with biomass of the cyanobacteria *Nostoc commune*, *Scytonema hyalinum* and *Tolypothrix distorta* and the combination of these species, carried out in three different ecosystems in southeastern Spain, highlighted that after three months, the cyanobacteria had a good development, all inoculated soils showed a cyanobacterial coverage of up to 50%, a lower albedo and a higher chlorophyll content. The inoculation with cyanobacteria also improved soil functions, contributing to the accumulation of nitrogen and carbon in the soil. Among the inoculation treatments, *N. commune* and the mixture of all three species promoted the highest cyanobacterial coverage, chlorophyll content, and surface darkening, as well as an increase in organic carbon and total nitrogen in the soil, highlighting their excellent performance in the development of biocrust (Román et al.; 2018).

A specific approach must be taken while selecting cyanobacterial biofertilizers for rice fields, which are generally much more favorable for their development, taking into account the fact that sufficient humidity benefits the activity of cyanobacteria. Research carried out on some rice fields has highlighted the fact that the species *Nostoc linckia*, *N. muscorum*, *Gloeotheca rupestris*, *Anabaena variabilis*, *Cylindrospermum michailovskoense*, *Gloeotrichia natans*, and *Microcystis aeruginosa* f. *pseudofilamentosa* dominate, and the species *Merismopedia tenuissima*, *M. punctata*, *Oscillatoria limosa*, *O. tenuis*, *O. amoena*, *Spirulina meneghiniana*, *Phormidium retzii*, *Lyngbya ampliclavata*, *Nostoc punctiforme*, *N. muscorum* have

the weakest development; this fact indicates that they can serve as fertilizers for the lands in question (Kuchkarova et al., 1981; Shtina et al., 1966).

The analysis of the indicator of the spreading of soil cyanobacterial species, according to research conducted since the beginning of the 20th century, highlights the most representative taxonomic units that inhabit the soils of the European and Asian regions: the *Chroococcales* family with the genera *Microcystis* — 9 species; *Aphanothece* — 6 species; *Gloeocapsa* — 13 species; the *Nostocales* family with the genera *Nostoc* — 21 species; *Anabaena* — 19 species; *Cylindrospermum* — 14 species; *Tolypothrix* — 6 species; *Calothrix* — 8 species and the *Oscillatoriales* family with the genera *Oscillatoria* — 50 species; *Phormidium* — 52 species; *Lyngbya* — 28 species; *Schizothrix* — 14 species; *Microcoleus* — 9 species; *Plectonema* — 15 species (Golerbah, Ştina 1969). The results of this research enable us to conclude that the use of representatives from these genera as biofertilizers can yield beneficial results without significant disruptions to algal and cyanobacterial biodiversity.

Recent scientific research highlights the fact that the most widespread cyanobacteria on the Earth, identified based on the study of specialized scientific articles, are the following species: *Nostoc* sp. (found in the USA, China, Iran, Australia, Israel, Germany, Brazil, Spain, South Africa, Mexico, Argentina, Chile, India, Iceland, Poland, Norway/Iceland and Portugal), *Leptolyngbya* sp. (identified in the USA, Australia, Spain, Germany, South Africa, Brazil, Austria, Chile, China, Iceland, Iran, Mexico, Morocco and Norway/Iceland), *Microcoleus* sp. (found in the USA, Spain, China, South Africa, Australia, Botswana, Chile, Iceland, India, Israel and Norway/Iceland), *Phormidium* sp. (found in Spain, South Africa, Australia, USA, China, Botswana, Chile, India, Iran, Iraq, Israel, Mexico and Norway/Iceland), *Oscillatoria* sp. (widespread in China, Iran, USA, Australia, Argentina, Botswana, Brazil, India, Iraq, Israel and Norway/Iceland), *Microcoleus steenstrupii* (found in USA, Spain, Israel, Botswana, Brazil and South Africa), *Microcoleus vaginatus* (USA, China, Israel, Iran, Spain, Brazil, Germany, Argentina, Austria, Chile, Iceland, Mexico, Poland and South Africa), *Scytonema* sp. (USA, Australia, China, Israel, Spain, Botswana, Brazil, Ecuador, India, Iceland, Iran and South Africa), *Chroococcidiopsis* sp. (USA, Spain, South Africa, Brazil, China, Mexico, Australia, Chile, Iran

and Ukraine), *Tolypothrix* sp. (USA, China, Iran, Spain, Australia, Brazil, Israel, Poland and South Africa), *Nostoc commune* (Spain, Australia, Argentina, China, Iran, Ecuador, Germany, Mexico, Poland and USA), *Schizothrix* sp. (Australia, Israel, Spain, USA, Brazil, India, Iran, Mexico and Morocco), *Calothrix* sp. (USA, Brazil, Israel, Austria, Iran, South Africa and Spain), *Lyngbya* sp. (USA, China, Germany, Argentina, India, Iran and Morocco), *Chroococcus* sp. (Australia, Brazil, India, South Africa, Israel, Mexico, Morocco, Poland and Spain), *Microcoleus paludosus* (Australia, USA, Botswana, China, Spain and South Africa), *Scytonema hyalinum* (Spain, Australia, Botswana, Brazil, Mexico and USA), *Tolypothrix distorta* (Spain, Australia, Mexico and South Africa), *Anabaena* sp. (Australia, China, India, Iran, Mexico, Portugal and USA), *Synechococcus* sp. (USA, Australia, Botswana, India and Mexico) *Trichocoleus* sp. (USA, Spain, China, Germany and Iran), *Phormidium tenue* (China) (Dal-Ferro et al., 2024).

The analysis of the distribution of soil cyanobacteria highlights the most adaptable species and genera, such as *Nostoc*, *Anabaena*, and *Phormidium*. They can be effectively used as biofertilizers to improve soil fertility and support plant growth, even in degraded or arid ecosystems. Precise knowledge of their ecological characteristics remains essential for practical application in agriculture.

Selected cyanobacteria as biofertilizers and their application doses. The cyanobacteria as biofertilizers are selected with consideration of the previously mentioned criteria and the specifics of these organisms.

To highlight a general law for the spectrum of cyanobacterial groups with potential for selection as biofertilizers for agricultural lands, we set out to analyze the genera of cyanobacteria that dominate in the agricultural soils of the Earth. The analysis in question was carried out only within the limits of the scientific sources studied in this article, taking into account the scientific results published by A.A. Elenkin (Elenkin, 1949), which can, however, be supplemented, as appropriate, with other scientific results. The taxonomic classification of cyanobacterial species was carried out according to the blue-green algae determinant (Elenkin, 1949; Golerbakh et al., 1953).

The data, presented in *Table 1*, allow for the conclusion that the most widespread cyanobacteria with abundant development on the Earth's soils belong to the following genera: *Microcystis*, *Chroococcus*, *Nostoc*, *Anabaena*, *Cylindrospermum*, *Tolypothrix*, *Calothrix*, *Oscillatoria*, and *Phormidium*. The representatives of soil cyanobacterial species from other genera can be used as biofertilizers, but preference should be given to the abovementioned genera.

The cyanobacterial species mentioned in the *table 2* were selected based on their habitat, abundance, and

Table 1. *Cyanobacterium* genera in arable soils of the Earth

Genera	Regions of the Earth					
	Africa	North America	South America	Asia	Europe	Ocenia
<i>Microcystis</i>	+	+	+	+	+	+
<i>Aphanothece</i>	-	+	-	+	+	-
<i>Gleocapsa</i>	-	+	-	+	+	-
<i>Nostoc</i>	+	+	+	+	+	+
<i>Anabaena</i>	+	+	+	+	+	+
<i>Cylindrospermum</i>	+	+	+	+	+	+
<i>Tolypothrix</i>	+	+	+	+	+	+
<i>Calothrix</i>	+	+	+	+	+	+
<i>Oscillatoria</i>	+	+	+	+	+	+
<i>Spirulina</i>	+	+	-	+	+	-
<i>Phormidium</i>	+	+	+	+	+	+
<i>Lyngbya</i>	+	+	+	+	+	+
<i>Schizothrix</i>	+	+	+	+	+	+
<i>Microcoleus</i>	+	+	+	+	+	+
<i>Plectonema</i>	-	+	-	+	+	-

Note: The “+” sign indicates the presence of the cyanobacterial genus in the agricultural soils under analysis. The “-” sign indicates the absence of the cyanobacterial genus in the agricultural soils under analysis.

distribution on the Earth, and, in our opinion, they can serve as a source of biofertilizers for the cultivation of various crops on the soil.

The studies, conducted by the authors on different subtypes of chernozem (typical, common, leached) under various crops (sunflower, wheat, barley, corn, rape, pea) in the central and southern regions of the Republic of Moldova in 2010–2025, demonstrated that algae have direct and indirect impact on soils and functioning of the soil ecosystem (pedogenesis) and the “soil–plant” system.

At the same time, based on our research, but also on those present in the specialized literature, we believe that the most optimal results can be obtained with the combined application of these species, and the selection of the composition and quantity specific to each species should consider the floristic composition of cyanobacteria and soil algae specific to agricultural lands specific to geographical areas, firstly, not to create disturbances in local populations. It is advisable to include nitrogen-fixing cyanobacterial species in the composition of combined cyanobacterial biofertilizers, considering that these species have the ability to adjust the nitrogen content in the soil according to the ecosystem needs, as demonstrated in our previous studies.

When applying cyanobacterial fertilizers, special attention must be paid to the application doses. First-

ly, high doses, starting from several tons per 1 ha of land, generate high cultivation costs and make agriculture unprofitable, and secondly, they can cause adverse effects manifested by overpopulation of the territory and its biological pollution. Therefore, it is necessary to select the optimal doses for a unit of area. To answer this question more accurately, it is necessary to identify, study, and understand the soil ecosystem, and the simplest example in this regard is the natural phenomenon of “soil bloom”. If we make an intuitive calculation based on these natural phenomena, then, according to the results presented by Domracheva L.I., the total biomass amount in the case of soil flowering monitored for 10 years was a minimum of 0.049 mg/cm², a maximum of 2.588 mg/cm², and an average of 1.318 mg/cm² (Domracheva, 1998).

After conversion into units of kg/ha, these figures would present the following results: minimum — 4.9 kg/ha, maximum — 258.80 kg/ha, and on average — 131.80 kg/ha. Other studies, specific to this field, indicate that the total biomass of cyanobacteria on an area of 1 ha can reach 1,500 kg/ha or even more (Shtina & Golerbakh, 1976).

In our opinion, based on perennial studies, the amount of biofertilizers of dominant soil cyanobacteria that can be administered to an area of 1 ha should fluctuate within the limits of 5–258 kg/ha, which

Table 2. Cyanobacterial species recommended for use as biofertilizers on arable lands

Cyanobacterial genus	Recommended species
<i>Microcystis</i>	<i>M. pulvereae</i> , <i>M. sgrevillei</i> , <i>M. hansgirgiana</i> , <i>M. testacea</i> , <i>M. parietina</i>
<i>Nostoc</i>	<i>N. linckia</i> , <i>N. punctiforme</i> , <i>N. gelatinosum</i> , <i>N. microscopicum</i> , <i>N. commune</i> , <i>N. paludosum</i> , <i>N. minutum</i> , <i>N. microscopicum</i> , <i>H. foliaceum</i> , <i>N. flagelliforme</i>
<i>Anabaena</i>	<i>A. variabilis</i> , <i>A. sphaerica</i> , <i>A. cylindrica</i> , <i>A. oscillarioides</i> , <i>A. azollae</i> (when cultivating the plant <i>Azolla caroliniana</i>)
<i>Cylindrospermum</i>	<i>C. licheniforme</i> , <i>C. majus</i> , <i>C. punctatum</i> , <i>C. michailovskoense</i> , <i>C. stagnale</i> , <i>C. muscicola</i> , <i>C. minutissimum</i> , <i>C. catenatum</i> , <i>C. marchicum</i>
<i>Tolypothrix</i>	<i>T. tenuis</i> , <i>T. distorta</i> , <i>T. arenophila</i>
<i>Calothrix</i>	<i>C. elenkinii</i> , <i>C. clavata</i> , <i>C. gypsophila</i> (for soils, rich in Calyx)
<i>Oscillatoria</i>	<i>O. jenensis</i> , <i>O. amphibia</i> , <i>O. schultzei</i>
<i>Phormidium</i>	<i>Ph. foveolarum</i> , <i>Ph. molle</i> , <i>Ph. subcapitatum</i> , <i>Ph. tenue</i> , <i>Ph. bohneri</i> , <i>Ph. corium</i> , <i>Ph. lividum</i> , <i>Ph. autumnale</i> , <i>Ph. mucicola</i> , <i>Ph. curtum</i> (for Europe and Antarctica)
<i>Lyngbya</i>	<i>Ly. amplivaginata</i> , <i>Ly. kützingiana</i> , <i>Ly. martensiana</i> , <i>Ly. aeruginosa-coerulea</i>
<i>Schizothrix</i>	<i>S. rubra</i> , <i>S. friesii</i> , <i>S. cuspidata</i> , <i>S. lardacea</i> , <i>S. arenaria</i> , <i>S. delicatissima</i> , <i>S. thelephoroides</i> , <i>Sch. purpurascens</i> , <i>Sch. mülleri</i> , <i>Sch. lamyi</i> , <i>Sch. fuscescens</i>
<i>Microcoleus</i>	<i>M. vaginatus</i> , <i>M. paludosus</i>

may vary depending on the type of soil, geographical region, and degree of humidity.

CONCLUSIONS

Soil cyanobacteria are promising biofertilizers with multiple application due to their proven positive impact on the health of soils and crops. The selection of effective species remains a serious problem, thus, clear identification criteria were suggested in the study: dominance, spreading, high tolerance to environmental factors, high development rate, easy transition between the vegetative and dormant stages, minimum generation time and potential for industrial cultivation. 11 representative genera and 65 species of cyanobacteria were identified and recommended for various soil types, along with the optimal application rate (5–258 kg/ha) in the living form, to ensure sustainable soil fertility and crop productivity.

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**ПЕРСПЕКТИВНІ ВИДИ ЦІАНОБАКТЕРІЙ,
ЩО РЕКОМЕНДУЮТЬСЯ ЯК БІОДОБРИВА
ДЛЯ ҐРУНТІВ, ЯКІ ВИКОРИСТОВУЮТЬСЯ
ДЛЯ СІЛЬСЬКОГОСПОДАРСЬКОГО
ВИРОБНИЦТВА**

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Мета. Виявлення критеріїв та підбір видів ціанобактерій, які можуть бути використані як біодобрива для ґрунтів, що використовуються в сільськогосподарському виробництві. **Методи.** Використані специфічні методи синтезу, логічного аналізу і кореляції наукових результатів, порівняльний метод, систематизація, пояснення і дедукція. Польові дослідження проводилися протягом 2010–2025 рр. у центральній та південній частинах Республіки Молдова на чорноземах (типових, звичайних і вилугуваних) під сільськогосподарськими культурами (соняшник, пшениця, ячмінь, кукурудза, ріпак, горох). **Результати досліджень.** Встановлено критерії відбору бактерій, що вносяться в якості біодобрив на сільсько-

господарських угіддях Землі, що використовуються для культивування культурних рослин, а саме: домінування, поширення, висока толерантність до факторів природного середовища (без проміжних етапів акомодатії), мінімальний час генерації та потенціал промислового вирощування. Було ідентифіковано ціанобактерії, рекомендовані як біодобрива для ґрунтів, представлено їх таксономічне положення, від роду до виду. Найбільш репрезентативними родами ціанобактерій, рекомендованими в якості біодобрив для різних типів ґрунтів, є: *Microcystis*, *Nostoc*, *Anabaena*, *Cylindrospermum*, *Tolypothrix*, *Calothrix*, *Oscillatoria*, *Phormidium*, *Lyngbya*, *Schizothrix* і *Microcoleus*. Також визначено 65 видів ціанобактерій, представників домінуючих і поширених

у всьому світі родів, рекомендованих для використання в якості біодобрив. Встановлено оптимальну дозу ціанобактеріальних добрив (від 5 до 258 кг/га) та форму їх застосування, щоб забезпечити стійкість здоров'я ґрунту та сільськогосподарських рослин. **Висновки.** Ціанобактерії є перспективними біодобривами з встановленим впливом на здоров'я ґрунту та продуктивність сільськогосподарських культур. У дослідженні визначено критерії відбору ефективних видів та виокремлено рекомендовані роди та види для різних типів ґрунтів. Їх застосування в живій формі може підтримати родючість і стійкість агроecosystem

Ключові слова: ціанобактерії, біодобрива, ґрунти.