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Changes in the Structure of Soil Microscopic Fungi in the Territories of Yavoriv and Podorozhenie Sulfur Quarries

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ABSTRACT
The article presents the results of monitoring the soil mycobiota of sulfur quarries in LvivRegion. The dynamics of soil micromycete complexes as a result of their adaptation to the conditions of technozems, embryozems and zonal soils of sulfur quarries was studied. The increase in the number of colony-forming units (CFU) in the studied soils of the Yavoriv and Podorozhnie sulfur quarries over the years is specified, which indicates the active processes of decomposition of plant remains, the formation of stable processes of decomposition of cellulose and other complex compounds in the detrital block of the ecosystem. The change in the frequency of banding of selected species of micromycetes over the years was studied, depending on the content of SO_4^{-2} in the soil solution. The functional structure of soil micromycete communities after sulfur extraction was established. A decrease in the frequency of occurrence of pathogens and toxin-producing agents and an increase in the frequency of occurrence of species that actively participate in the transformation of organic remains, and also act as plant endophytes and participants in mycorrhizal symbiosis were recorded. The species composition of micromycetes that grew in the presence of SO_4^{-2} content in the soil solution, which exceeded the background level from 3.6% to 50%, was determined, the species-bioindicators of soil pollution with sulfur compounds were defined - *Fusarium oxysporum, Paecilomyces lilacinum, P. waksmanii, P. nigricans, P. funiculosum, Trichoderma viride, Cladosporium cladosporioides, C. herbarum, Aureobasidium pullulans, Humicola grisea, Ulocladium consortiale, Alternaria alternate, Mortierella ramanniana var. angulispora*. During 10 years of research a decrease in the content of SO_4^{-2} in soils was noted, which is associated with an increase in the biodiversity of soil micromycetes and an enrichment of the phytocenotic cover.

Keywords: bioindication, mycobiota, devastated soils, endophytes, sulfur quarries, phytocenosis.

INTRODUCTION

As a result of the decommissioning of a large number of native sulfur deposits on the territory of Ukraine, environmental problems have significantly increased. This fact is related to the slow restoration of ecological functions of vegetation in man-made landscapes. Today, the close connection of plants, animals, microorganisms and soil is maintained at various hierarchical levels of the structural and functional organization of this system.

However, the unity of soil and biodiversity determined by the evolution is quite vulnerable and can function in a balanced mode, only if the integrity of all its components and natural landscapes as a whole is preserved [Symochko et all., 2017; Hafiiak & Symochko, 2022]. In the process of self-restoration of soil and plant cover on devastated lands, the role of micromycetes in improving edaphic conditions is enhanced [Hurla & Oliferchuk, 2011; Hurla et al., 2012; Nazarovets & Oliferchuk, 2013; Nazarovets et al., 2014; Taras et al., 2014; Kopii et al., 2017; Oliferchuk et al., 2022].

The soils of the researched areas of the Yavoriv and Podorozhnie sulfur quarries were formed as a result of natural self-renewal of the soil and plant cover and are biogenically undeveloped and belong to embryozems. The soil cover of the territory of the Yavoriv and Podorozhnie sulfur quarries is represented by spatial combinations of different types of embryozems. The main features in their diagnosis are the presence of diagnostic horizons in soil profiles.

The variegation of physical soil properties during the examination of embryozems of sulfur quarries is reflected in the agrochemical properties of the newly formed soils. [Holeusov, 2004; Brovko, 2012; Hvozdiak et al., 2017].

Plants appear at their growth sites with endophytes inside the seed, then these endophytes release sugars and attract a huge community of commensal and mutalistic microorganisms that provide the plant with necessary services, such as increasing mineral absorption, nitrogen fixation, growth stimulation and protection against pathogens [Demyanyuk et al., 2017]. These plant microbiota are mainly located in the root system, which deposits up to 40% of the plant's photosynthetically fixed carbon in the rhizosphere, making this small zone around the roots one of the most energy-rich habitats on Earth [Symochko, 2020; Hafiiak & Symochko, 2022].

The nature of biodynamic transformations of organic matter is one of the objective indicators of productivity, stability and development of biocenoses. The volume of synthesis and destruction of organic substances are factors that determinethe level of organization of the biosphere, and the detrital block significantly surpasses the autotrophic block in terms of structural complexity and variety of functions [Symochko et al., 2017; Nagurskyy et al., 2022].

MATERIAL AND METHODS

The research was conducted at the National Forestry University of Ukraine. Soil samples were taken by the method of squares (10 × 10 m) at a depth of 0–25 cm in accordance with DSTU ISO.10381–6: 2015 and its ecological status was determined by bioindication and biotesting [DSTU 7847: 2015; DSTU ISO 10381–6: 2015; DSTU ISO 11269–2: 2002]. The procedure for the selection, preservation and transportation of soil samples was carried out according to standard methods. The number of micromycetes of the main ecological groups was determined according to DSTU 7847:2015 and the standard methods in microbiology of soil and water [Zvyagintsev, 1991; Tepper et al., 2004].

Determination of the color of the colonies, which is necessary for the description of the isolates, was carried out using the Bondarev scale and using the additive RGB model of Adobe Photoshop CS5. Statistical processing of the obtained results was carried out using generally accepted methods using Microsoft Excel and Statistica 9.0 programs.

The functional structure of groups of soil micromycetes was established using the correlation groups method [Borysova, 1988]. The statistical processing of the obtained results and all necessary calculations were performed according to the program developed at the Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine.

RESULTS AND DISCUSSION

Through 10 years, 250 soil samples were taken from the sulfur quarries of Lviv Oblast, from which about 1,700 isolates of fungi were isolated. After identification, they were assigned to 76 species of 31 genera. Dominant species and those that occurred frequently were used for further analysis.

In general, the mycocenoses of the studied ecotopes contained species that are described as typical for the meadow soils of Polissia and the Forest Steppe of Ukraine [Bylai et al., 1984]. A characteristic feature of the microflora of temperate and northern latitudes is the presence of a wide variety of species of the genus *Penicillium*, and a narrow spectrum of species of the family *Dematiaceae* and the partial presence of species of the genus *Fusarium*. Among mucoral fungi, meadows of temperate and northern latitudes are characterized by the constant presence of species of the genus *Mucor*. Regarding representatives of the species of the *Zygomycota* division, it should be noted that they were detected with a high frequency and were constantly isolated in 2011 from all the studied monitoring points of the Podorozhnie and Yavoriv sulfur quarries. In subsequent years, the frequency of its appearance decreased somewhat, and the species composition expanded. In the sulfur quarries, there was a tendency towards the presence of a wide range of species of the genus *Penicillium*, but the presence of a wide range of species of the genus *Aspergillus*, which is characteristic of the meadow mycoflora of southern latitudes, was also typical. These are the species *Aspergillus niger*, *A. fumigatus,* and *A terreus,* which occurred in the investigated ecotopes with varying frequency but were constantly present. It should also be noted that the mycoflora of sulfur quarries contained species typical for protected areas. *Verticillium album* and *Cladosporium brevi-compactum*, which were found on the embryozems of the Podorozhnie Sulfur Quarry, were isolated from the herbaceous and sedge associations of the reserves. Species typical for fruit plantations were also identified at the studied territories. The study of the mycoflora of the soils of fruit plantations in Ukraine has been conducted since 1967, and it was studied in all soil and climate zones of Ukraine (Polyssia, Forest Steppe, Steppe, Precarpathian region and Transcarpathia). The fungi species found in the fruit orchards in the Podorozhny and Yavorov sulfur quarries were as follows: the species *Penicillium roseopurpureum, P. citrinum, P. funiculosum, Aspergillus terreus, A. niger, A. fumigatus,* which are widely distributed throughout the profile of garden soils.

In conclusion, we can say that the species composition of micromycetes of sulfur quarries soils does not correspond to the principle of zonation, but depends on the peculiarities of the morphological and functional structure of fungi, the possibility of colonization of various types of substrates.

Most types of soil micromycetes are distinguished byexceptionaly active systems of oxidizing and glycolytic enzymes, and are characterized by the high efficiency of the use of organic energy sources. Along with this, many soil micromycetes are auxotrophic in relation to amino acids, vitamins, coenzymes and other metabolically important compounds, that is, they are able to synthesize it using mineral and carbon compounds. This ability determines the appropriate functions of these organisms and causes the formation of their specific associations, which we observed when studying the sulfur quarries of Lviv Region. The associative activity of these organisms creates appropriate compounds for other organisms (plants, bacteria) and thereby ensures a high level of metabolic adaptation. Most species of the class of deuteromycetes are characterized by a heterogeneous structure of the nuclear apparatus, a variety of sexual and asexual reproduction and alternation of haploid and diploid phases in the life cycle, heterokaryosis, parasexual process, etc., which causes their high variability, heterogeneity of the intraspecific population, and the ability to adapt to extreme environmental conditions.

The role of endophytes in the restoration of plant cover in sulfur quarries

We observed an increase in the number of eming units (CFU) on devastated soils. In ten years, the number of viable diaspores in the zonal

Table 1. The number of colony-forming units (CFU) in the investigated soils of the Yavoriv and Podorozhnie sulfur quarries

Yavoriv sulfur quarry					Podorozhniesulfurquarry				
Monitoring points	2011		2022		Monitoring points	2011		2022	
	0-2 cm	8-10 cm	0-2 cm	8-10 cm		0-2 cm	8-10 cm	0-2 cm	8-10 cm
ZH1	$3.4×10^3$	$1.2×10^3$	$1.8×10^4$	$2.7×10^4$	ZH4	$1.4×10^4$	$1.7 ×10^4$	$2.1 ×10^4$	$3.7 ×10^4$
ZH2	$2.7×10^3$	$3.2×10^3$	$2.5×10^4$	$2.9×10^4$	ZH7	$2.2×10^4$	$1.8×10^5$	$3.2 ×10^5$	$5.6 ×10^5$
E3	$1.7 ×10^3$	$2.1 ×10^3$	$1.9×10^4$	$2.1×10^4$	E3	$7.8×10^3$	$1.4×10^5$	$5.7×10^5$	$3.2 ×10^4$
E4	$1.8 ×10^3$	$1.6 ×10^3$	$1.7×10^4$	$2.3×10^4$	E4	$4.2 ×10^3$	$2.7 ×10^4$	$4.3×10^4$	$3.2×10^4$
E7	$2.5 ×10^3$	$1.8 ×10^3$	$2.2×10^4$	$2.7×10^4$	E7	$3.2×10^3$	$2.2 ×10^3$	$3.1×10^3$	$2.5×10^3$
T5	$2.4×10^2$	$3.2×10^2$	$7.4×10^2$	$9.5×10^2$	T5	356	517	$1.5 ×10^2$	$1.8×10^2$
T6	$1.8×10^2$	$2.7×10^2$	$6.7×10^2$	$8.7×10^2$	T7	678	712	$1.4×10^2$	$1.7×10^2$

soils of both quarries increased by an order of magnitude (Table 1). We observe the same effect on embryozems. Only on the technogenic soils of sulfur quarries, the number remains the same or does not increase significantly.

The increase in the number of CFU indicates the active processes of decomposition of plant remains that get into the soil and the formation of sustainable processes of decomposition of cellulose and other complex compounds in the detrital block of the ecosystem. The composition of the substrate and the activity of enzymes, the competitive ability of this type of fungi make up a complex of physiological properties that allow assimilation of the substrate. Plants and plant substrates create both relative constancy and dynamism of the soil environment. The composition of root secretions and plant residues changes not only cyclically, but also seasonally. At the same time, the various use of the substrate affects directly or indirectly not only the change in the species composition of soil micromycetes, but also the germination of spores, growth, reproduction, and survival of individual species.

It should be noted that over the years, the species composition of the isolated soil micromycetes of the Yavoriv and Podorozhnie sulfur quarries has been characterized by a greater diversity of species and genera. Representatives of the order *Mucorales* - species of the genera *Mucor, Rhizopus, Mortierella* - were constantly found in the studied areas on zonal soils, embryozems and technological soils. Among them, the species *Mucor hiemalis* and *Mortierella isabelline* took the leading place in terms of frequency of appearance. The order *Mucorales* was represented by 5 species of 3 genera. Since the species of this order were almost constantly found in the embryozems, technological soils and zonal soils of the investigated areas of sulfur quarries, we followed the frequency distribution of the species of the above three genera for ten years, and found that the technological soils were distinguished as possessing species mainly of the genera *Mucor, Rhizopus*, and the species of the genus *Mortierella* were found with a high frequency of appearance mainly on embryozems and zonal soils.

Analyzing the change in the appearance frequency of selected species by years (Table 2) depending on the content of SO_4^{-2} in the soil solution, we found a decrease in the appearance frequency of *Penicillium roseopurpureum*, *Aspergillus fuumigatus*, *A. niger, Fuzarium oxysporum,* which are pathogens and toxin-producing species, and *Oidiodendron ehinulatum*, which is an indicator of soil pollution with sulfur. Along with this, we observed an increase in the frequency appearance of species *Cladosporium cladosporioides, Trichoderma viride, Trichoderma lignorum, Humicola grisea,* species that participate actively in the transformation processes of organic remains.

It should be noted that the role of micromycetes, which are widely distributed and represented by soil isolates, can also act as endophytes of plants and participants in mycorrhizal symbiosis - species of the genus *Trichoderma*.

Species of the genus *Trichoderma* have high antagonistic activity against pathogens, and during these 10 years we have observed a decrease in the number and species diversity of pathogens

Table 2. Dominant (50% or more appearance frequency) and constantly occurring (more than 30% appearance frequency) fungi species of the Yavoriv and Podorozhnie sulfur quarries

N	A type of fungus	Podorozhnie sulfur quarry							Yavoriv sulfur quarry						
		T5	T6	E1	E2	E3	ZH4	ZH7	T5	T6	E3	E4	E7	ZH1	ZH2
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Division Zygomycota															
1	*Absidia glauca* Hagem	-	-	23	1	2	2	3	-	-	1	2	12	2	-
2	*Absidiablakesleana* Lendr.	-	-	-	-	-	-	-	-	-	2	3	-	-	-
3	*Mortierella alpine* Peyronel	-	-	1	-	2	-	3	-	-	2	1	-	12	23
4	*Mortierella elongate* Linnemann	-	-	-	-	-	-	-	-	-	-	2	-	2	3
5	*Mucor racemosus* Fresenius	2	-	-	1	2	12	23	-	-	-	-	-	-	-
6	*Mucor globosus* Fischer	-	-	-	-	-	2	3	-	-	-	-	-	-	-
7	*Mucor hiemalis* Wehmer	123	12	123	123	23	3	3	12	123	123	13	3	23	3
8	*Mortierella ramanniana var. angulispora* (Naumov) Linnem	12	12	1	1.2	1	3	3	1	1	1	1	12	3	3
9	*Rhizopus nigricans* Fhrenb.	1	1	12	12	12	-	-	1	1	1	12	12	123	3
10	*Rhizopus oryzae* Went et Prin. Geerligs	-	-	-	-	-	2	-	-	-	2	2	-	-	3

Table 2. Cont. Dominant (50% or more appearance frequency) and constantly occurring (more than 30% appearance frequency) fungi species of the Yavoriv and Podorozhnie sulfur quarries

Division Ascomycota light-colored															
9	*Aspergillus terreus* Thom	-	-	1.2	2	3	2	23	-	-	1	13	2	1	-
10	*A. ustus* Bainier	-	-	-	1	2	1	-	-	-	-	1	2	2	1
11	*A. niger v.*Tieghem	123	23	1	1	1	2	1	1	2	1	12	1	1	2
12	*A. fumigatus*Fres.	12	123	1	3	3	2	2	12	12	2	3	2	1	2
13	*A. repens* (Cda.)Sacc.	-	-	13	23	1	3	13	-	-	2	12	1	2	23
14	*A. ochraceus* Wilhelm	-	-	12	123	1	-	1	-	-	12	1	12	3	13
15	*Acremonium strictum* Gark	-	-	1	-	3	12	1	-	-	2	3	12	-	3
16	*Cylindrocarpon destructans* (Kins)	-	-	-	-	-	12	2	-	-	-	-	-	-	-
17	*Chaetomium spirale* Zopt	-	-	-	-	-	12	13	-	-	-	-	-	-	-
18	*Fusarium oxysporum* Schlecht	123	23	12	12	13	1	1	12	1	12	123	2	2	13
19	*F. culmorum* (W. G. Sm.) Sacc.	-	-	1	-	2	12	1	-	-	1	2	-	2	3
20	*F. moniliforme* Scheld	3	3	1	2	-	2	1	3	3	1	21	-	123	12
21	*F. solani* (Mart) App.et Wr.	-	-	-	-	-	-	-	-	-	12	13	1	12	3
22	*Paecilomyces* sp.	3	23	12	2	1	1	2	3	3	1	23	1	2	1
23	*Paecilomyces lilacinum* (Thom) Samson	1	1	12	13	1	1	2	23	1	1	1	2	12	1
24	*Penicillium roseopurpureum* Dierck	1	2	12	13	1	-	-	123	2	13	2	12	-	-
25	*P. waksmanii* Zaleski	12	12	12	2	1	-	-	12	23	2	1	3	-	-
26	*P. nigricans* (Bainier) Thom	123	12	12	1	12	2	2	123	23	1	1	2	3	1
27	*P. funiculosum* Thom	2	12	12	23	3	-	1	1	12	1	2	2	-	-
28	*P. crustozum* Thom	-	-	12	1	2	2	3	-	-	2	3	1	13	23
29	*P. brevi-compactum* Dierckx	-	-	1	2	12	3	3	-	-	23	3	2	1	1
30	*P. chryzogenum* Thom	-	-	-	1	2	2	12	-	-	1	-	-	2	2
31	*P. ochro-chloron* Biourde	-	-	1	12	3	2	3	-	-	3	2	-	1	2
32	*P. lilacinum* Thom	-	-	1	12	2	12	2	-	-	1	2	3	1	3
33	*P.* citrinum Thom	-	-	1	1	2	12	2	-	-	1	-	-	1	2
34	*P. spinulosum* Thom	-	-	1	1	2	3	23	-	-	1	23	2	3	3
35	*P. lividum* Westl.	-	-	12	123	2	3	1	-	-	2	12	3	1	3
36	*P. rubrum* Stoll	-	-	23	1	3	2	3	-	-	1	2	3	3	3
37	*P. raciborskii* Zaleski	-	-	-	-	-	12	3	-	-	1	2	12	3	2
38	*P. luteum* Zukal	-	-	-	1	-	12	3	-	-	1	2	-	1	2
39	*Trichotecium rozeum* Lk.	-	3	2	3	3	2	1	-	3	3	2	3	1	3
40	*Trichocladium asperum* Harz	-	-	-	-	-	-	-	-	-	123	3	23	2	3
41	*Pestalotia hartigii* Tubent	-	-	-	-	-	-	-	-	-	-	3	2	3	12
42	*Trichoderma viride* (Pers. Et S.F. Gray.)	13	12	123	123	123	123	123	23	123	123	123	23	3	123
43	*T. lignorum* (Todle) Has.	-	-	2	3	3	23	23	-	-	23	2	3	3	2
44	*T. harcianum* Rifal	3	-	23	1	3	2	2	3	-	-	2	3	1	3
Dark colored															
45	*Aureobasidium pululans* (de Bary) Arnaud	12	23	1	23	1	2	3	123	1	23	2	3	1	2
46	*Alternaria alternate* (Fr.) Keissler	-	2	2	1	3	2	3	-	-	1	-	-	1	-
47	*Cladosporium cladosporioides* (Fres.) de Vries	12	3	1	2	2	3	2	12	3	2	1	2	1	3
48	*C. herbarum* (Pers.) Link ex Gray	13	2	2	3	1	23	1	3	3	3	1	2	2	2
49	*Humicola grisea* Traaen	3	3	2	-	1	2	2	3	2	1	2	3	1	2
50	*Oidiodendron echinulatum* Barron	1	-	2	1	-	-	-	12	23	12	2	23	-	-
51	*Ulocladium consortiale* (Thum) Simmons	3	2	2	3	2	12	2	3	2	12	2	2	-	-
52	*Torula herbarum* (Pers.) Link	-	-	3	-	-	2	1	-	-	3	1	3	2	1
53	*Phoma pomorum* Thum.	-	-	2	3	2	2	1	-	-	2	3	-	3	2
54	*Phoma glomerata* (Corda) Wr. et Hochap.	3	-	1	2	-	2	1	1	-	-	-	1	2	1
55	*Phoma* sp.	-	-	3	2	3	2	32	-	-	-	-	-	1	2
56	*Mycelia sterilia (white)*	123	123	1	-	-	-	-	123	123	-	-	-	-	-
57	*Mycelia sterilia (darc)*	123	123	-	-	-	-	-	123	123	-	-	-	-	-

Note: 1 – 2011 year, 2 – 2016 year, 3 – 2021 year.

in the territories of zonal soils, embryozems and technological soils of the Yavoriv and Podorozhnie sulfur quarries. The obtained results indicate the gradual formation of strains that adapt to the increased content of SO_4^{-2} in the soil solution in the respective species populations. Thus, at the strain level, a number of representatives of the order *Mucorales* and the division*Ascomycota* adapted to the increased level of background concentrations of SO_4^{-2} in the soil.

We recorded the greatest species diversity among fungi of the *Ascomycota* division. Among them, species of the genera *Penicillium, Aspergillus, Fuzarium* occupied a dominant position. In addition, as a part of soil biota of the Yavoriv-sulfur quarry, we recorded the appearance of such species as *Oidiodendronehinulatum* and *Ulocladium catenulatum*, which were not found in the zonal soils of the Yavoriv and Podorozhnie sulfur quarries, but they were constantly present in embryozems and technological soils. Experimental studies have shown that under the influence of high levels of increased SO_4^{-2}content in the soil solution, which corresponds to certain gradations of the condition and optimal change of microbocenoses in the sod-podzolic soils of the YavorivSulfur quarry, there is a transformation of the micromycete complex structure and the accumulation of toxic species that are not typical for podzolic soils; primarily these were the representatives of the genus *Aspergillus, Paecilomyces,* phytopathogens *Fusarium (F.oxysporum)* and dark-colored melanin-containing deuteromycetes of the *Dematiaceae* family. The same tendency is typical for the soils of the Podorozhnie Sulfur Quarry, but to a much lesser extent, since the forest vegetation and climate conditions of the region are much more favorable for the development of vegetation. It is also important to note the fact that there are sharp changes in the species diversity of soil micromycetes of the Yavoriv and Podorozhnie sulfur quarries, where the content of SO_4^{-2}in the soil solution is 50 times higher than background concentrations, compared to those territories where it is 4-7 times, higher background concentrations were not observed, which confirms the strain adaptation of species and genera of micromycetes to extreme environmental conditions.

It should be noted the fact that the natural and forest vegetation conditions of quarries after sulfur production differ little from each other. A landfill is located near the Yavoriv sulfur quarry, and about 300 hectares of solar panels are located on the shores of a man-made lake filled with water. The territory of the Podorozhnie sulfur quarry is located near the village, there are no other technogenic factors.

Absidia glauca, Mortierella alpine were found on embryozems and zonal soils of the Podorozhnie and Yavoriv sulfur quarries - species typical for sod-podzolic, gray forest soils, southern chernozems, dark chestnut soils, and meadow chernozems were also isolated from the soils of orchards. The species *Absidiablakesleana* was previously isolated from protected areas where the phytocenosis was dominated by vetch and creeping heather. In the technogenic areas of the Yavoriv Sulfur Quarry, this species was isolated from embryozems in 2016 and in 2021 - from places where the Canadian goldenrod species was dominant. *Mortierella elongate* is a species that is characteristic for sod-podzolic, brown and gray forest soils, as well as all types of chestnut soils. With a frequency of more than 30%, it was found on embryozemsand zonal soils of the Yavoriv sulfur quarry. *Mucor racemosus* was encountered with a frequency of more than 30% at the Podorozhniequarry. In natural landscapes, it was isolated from sod-podzolic soils, sod-carbonate, brown and gray forest soils, all types of chernozems. On devastated soils, it was isolated from technological soils, on which primary plant successions were formed in 2016. It was typical for embryos and zonal soils of the studied areas. *Mucor globosus,* a species typical for brown forest soils and chernozems, was isolated from zonal soils of the Podorozhnenska quarryin 2016 and 2021. *Mucor hiemalis* is a satellite species. It occurs in all types of soil, under almost all types of vegetation, described as the dominant species in places with a high level of radioactive contamination of 37 and 3.7x106 Bq/kg in the 10-kilometer exclusion zone of the Chernobyl nuclear power plant in 1986-1988 [Zhdanova et al., 2013]. In the ecotopes studied by us, it was isolated with a frequency of 50% and higher from technological soils and embryozems, where the content of SO_4^{-2} in the soil solution exceeded the level of background concentrations from 1.5 to 50 times. *Mucor hiemalis* was constantly found in the zonal soils of the Podorozhnie and Yavoriv sulfur quarries, but the frequency of its occurrence decreased over the time to 10-15%, respectively, due to the increase in the biodiversity of micromycete species. *Mortierella ramannianavar.angulispora* was found in technozems of both quarries with a frequency higher than 30%, where the content of SO_4^{-2} in the soil solution exceeded the background level by 44-50 times (monitoring points E2 and T5 - Podorozhne, T5, T6, E7 - Yavoriv). Information that this species was isolated from soils where radiation doses were 37, 3700, 3.7-105 Bq/kg was previously described [Zhdanova et al., 2013]. We offer the species *Mortierella ramanniana var. angulispora* from the division Zygomycota to be identified as a bioindicator species for various types of technogenic pollution. The species *Rhizopus nigricans* -satellite and *Rhizopus oryzae* typical for dark chestnut soils and meadow chernozems were isolated from the soils of the Podorozhnie and Yavoriv sulfur quarries among the representatives of the same division.

Among the light-colored species of the *Ascomycota* division, *Aspergillus* and *Penicillium* species were found with high frequency. Most of the selected species are typical for different soil types, such as dark gray forest, light gray forest, meadow, sod-podzolic, common chernozem and chestnut soils. These are *Aspergillus terreus*, *A. ustus, A. fumigatus, A. repens, P. brevi-compactum, P. chryzogenum, P. ochro-chloron, P. raciborskii* species. Meadow vegetation prevails on spoil tips, and the soil constantly contains species of fungi characteristic of the meadow vegetation of the Forest Steppe. Among them, there are *P. crustozum, P. citrinum, P. lilacinum, P. spinulosum, P. rubrum, T. lignorum, T. harcianum, F. moniliforme, Phoma sp*. But there were also species which are typical representatives of other habitats. *Pestalotia hartigii,* a representative of brown forest soils, was isolated by us from the zonal soils of the Podorozhnie Sulfur Quarry. *Cylindrocarpon destructans* and *F. solani*, which are representatives of dark chestnut soils, were also found on zonal soils and were isolated from the embryozemes of the Podorozhnie sulfur quarry. *Trichocladium asperum* was also isolated - a unique species that is characteristic of the territories of the Podorozhnie Sulfur Quarry, where partial phytoremediation using lupine was carried out. *Trichotecium rozeum* and *Paecilomyces sp.*the species *Aspergillus ochraceus* and *Acremonium strictum* were constantly isolated from the territories of the monitoring points of both quarries, where the primary successions of phytocenoses were formed with the participation of woody vegetation, in which birch was the main representative. *Chaetomium spirale,* a representative of carbonate chernozems, was isolated from the zonal soils of the Podorozhnie Sulfur.

Some species of the genera identified by us, which were often found atthe areas with different SO_4^{-2} content in the soil solution, were also described for areas with a high level of radioactive contamination [Zhdanova et al., 2013]. *Penicillium roseopurpureum,* with an appearance frequency of more than 50%, was found at areas with SO_4^{-2} content in the soil solution, which was 8.0-48.6 times higher than the background level. The same

Table 3. Species of micromycetes-bioindicators for various types of xenobiotics in the soil

Fungispecies	Content SO_4^{-2} (FR 160 mmol in 100 g)		Soil radioactivity Bk/kg (Zhdanova)
	the lowest	highest	
Mortierella ramanniana var. angulispora (Naumov) Linnem	1215 (7.6)	8032 (50.8)	37; 3700; 37×10^5
Penicillium roseopurpureum Dierck	1287 (8.0)	7780 (48.6)	$37\text{-}3.7\times10^6$
P. waksmanii Zaleski	168 (1.4)	8032 (50.8)	3.7×10^4
P. nigricans (Bainier) Thom	-	-	370; 37×10^5
P. funiculosum Thom	653 (3.6)	8032 (50.8)	370; 3700; $37\times10^4\text{-}37\times10^6$
Trichoderma viride (Pers. Et S.F. Gray.)	168 (1.4)	8032 (50.8)	$37\text{-}3.7\times10^6$
Cladosporium cladosporioides (Fres.) de Vries	-	-	$37\text{-}3.7\times10^5$
C. herbarum (Pers.) Link ex Gray	-	-	37
Aureobasidium pululans (de Bary) Arnaud	342 (2.1)	6554 (40.9)	37
Humicola grisea Traaen	168 (1.4)	7067 (44.1)	37
Ulocladium consortiale (Thum) Simmons	168 (1.4)	7780 (48.6)	37
Alternaria alternate (Fr.) Keissler	168 (1.4)	664 (4.1)	$37\text{-}3.7\times10^7$
Paecilomyces lilacinum (Thom) Samson	168 (1.4)	8032 (50.8)	370; 3.7×10^5
Fusarium oxysporum Schlecht	342 (2.1)	8032 (50.8)	$3.7\times10^4\text{-}3.7\times10^7$

species was found with a higher frequency in the territories where radiation doses ranged from 370 to 3.7x106 Bq/kg (Table 4). *Fusarium oxysporum, Paecilomyces lilacinum, P. waksmanii, P. nigricans, P. funiculosum, Trichoderma viride, Cladosporium cladosporioides, C. herbarum, Aureobasidium pullulans, Humicola grisea, Ulocladium consortiale, Alternaria alternate, Mortierella ramanniana var. angulispora* were dominant on all technogenic soils of the Podorozhnie and Yavoriv sulfur quarries. All these species grew in the presence of SO_4^{-2} content in the soil solution, which exceeded the background level from 3.6% to 50% (Table 3).

Regarding the change in the frequency of appearance of species by years, we can state the following: species that were found at the territories with a high content of SO_4^{-2} (above 50%) in the soil solution in 2011 were found in 2021 already with a frequency of appearance of 30% and below. Instead, the species diversity of micromycetes in the studied territories increased. The representatives of the *Mucedinaceae* family were the most numerous in terms of species diversity. Among them, the dominant position was occupied by species of the genus *Trichoderma*. During the study, the species of this genus were characterized by resistance to different SO_4^{-2} content in the soil, from 1.4 excess of the background level to over 50% (Table 5).

Among the species of the *Penicillium* genus, representatives of the *Monoverticillata* section – *Penicillium roseopurpureum* – dominated in all years. *P. waksmanii, P. nigricans,* and *P. funiculosum* of the *Biverticillata-symmetrica* section were among the representatives of the *Asymmetrica* section of this genus. A decrease in the frequency of the strains of the indicated species was observed over the years against the background of an increase in the species biodiversity of the genus *Penicillium*.

The order *Acervulales* was represented by species of the genus *Fusarium*, among which only the species *Fusarium oxysporum* was found in the areas with high SO_4^{-2} content. *F. culmorum* and *F. moniliforme* were found in ecotopes with medium SO_4^{-2} content in soils. We isolated the species *F. solani* only from the zonal soils of the Podorozhnie Sulfur Quarry.

Representatives of the *Coelomycetes* division found at the territories of sulfur quarries were the species *Phoma pomorum, Phoma glomerate* and *Phoma sp.* All strains of these species were confined to places with an average content of SO_4^{-2} in soils, and *Phoma sp.* was isolated only from the zonal soils of the Podorozhnie and Yavoriv sulfur quarries. Thus, we observe the presence of fungal species typical for temperate latitudes with different contents of SO_4^{-2} in the soil solution. During the first and fifth years (2011, 2016) of monitoring of the mycobiota of the soils of the studied sulfur quarries in Lviv Region, we recorded a decrease in the number of viable diaspores at points where the SO_4^{-2} content in the soil solution was above 50% of the background level.

In the territories where the content of SO_4^{-2} in the soil solution exceeded the background level by 50% in 2011, we recorded a qualitative and quantitative increase in the species of the *Zygomycota* division. In 2016, the situation changed towards a quantitative and qualitative excess of melanin-containing species at these territories, which allows us to expand the concept of industrial melanism, extending it to the mycobiota of sulfur-contaminated soils. It seems that the change in the dominance of species of the divisionZygomycota* in 2011 to the dominance of melanin-containing deuteromycetes in 2016 occurs due to two reasons:

- firstly, when the spoil tips were covered with minimal vegetation, and in some places resembled lunar landscapes, the outcrops were inhabited by species of the *Zygomycota* division.
- only over the years, when the vegetation died and a minimal layer of fertile soil was formed, there was a change in the dominance of genera species in the direction of melanin-containing deuteromycetes.

In 2021, the situation changed again, and we recorded an increase in the species diversity of light-colored species, but due to the expansion of the spectrum of species and genera that were isolated from the studied arreas.

We should also note a slight decrease in SO_4^{-2} content in soils over the years, which could be determied by the increase in the biodiversity of soil micromycetes and the enrichment of the phytocenotic cover (Table 4). Therefore, the processes of natural restoration of devastated soils and reduction of the level of sulfur pollution occur very gradually.

In the literature available to us, there are no studies that would illustrate a long-term change in the species diversity of soil micromycetes

Table 4. Decrease in SO_4^{-2} content in soils over the years at the monitoring points of the Podorozhnie and Yavoriv sulfur quarries (times, decrease according to the background level)

Yavoriv			Podorozhnie		
Monitoring points	2011	2021	Monitoring points	2011	2021
ZH1	1.8	1.4	ZH4	Not exceeding the MPC	Not exceeding the MPC
ZH2	2.1	1.7	ZH7	9.5	9.1
E3	4.6	4.0	E1	3.1	2.1
E4	5.7	5.1	E2	10.0	9.1
E7	50.8	48.6	E3	4.0	3.6
T5	44.0	40.9	T5	4.4	4.1
T6	8.0	7.5	T6	Not exceeding the MPC	Not exceeding the MPC

depending on the SO_4^{-2} content in soils. That is why we believe that the information obtained, where fungi are permanent components of biogeocenoses and are in the form of mycelium and spores, contains new data for science.

The structure of micromycete complexes in the soils of the studied ecotopes

A comparison of the mycobiota of soils with different contents of SO_4^{-2} in the soil solution, sampled in 2011-2021, which was typical for the Yavoriv sulfur quarry, showed a significant separation (low values of the coefficient V (Figure 1), which was preserved in the studied ecotopes, which manifested the most in soils with SO_4^{-2} content in the soil solution, which exceeded background concentrations by 40-50 times.

Ecotopes that differed by 1.8-4.4 times in SO_4^{-2} content in the soil solution were characterized by a high V coefficient. Itshows the reliable similarity of the mycobiota of these territories, which is typicalfor the studied points of the Podorozhnenska quarry.

	ЗГ$_2$	E$_3$	E$_4$	T$_6$	T$_5$	E$_7$
ЗГ$_1$	0.62	0.57	0.32	0.12	0.05	0.02
ЗГ$_2$		0.58	0.48	0.34	0.02	0.03
E$_4$			0.56	0.44	0.04	0.05
E$_4$				0.32	0.07	0.09
T$_6$					0.12	0.15
T$_5$						0.59

a

	T$_6$	E$_1$	E$_3$	T$_5$	ЗГ$_7$	E$_2$
ЗГ$_4$	0.68	0.57	0.52	0.52	0.46	0.34
T$_6$		0.51	0.44	0.42	0.40	0.32
E$_1$			0.61	0.58	0.41	0.24
E$_3$				0.67	0.42	0.35
T$_5$					0.35	0.47
ЗГ$_7$						0.58

b

Figure 1. Similarity coefficients of the species compositions of micromycetes isolated from soils of different degrees of sulfur pollution (a – Yavoriv Sulfur quarry, b – Podorozhnie Sulfur quarry)

Table 5. Species composition of micromycetes and its frequency (%) in the soils of Yavoriv and Podorozhnie sulfur quarries

No.	Fungi species	Podorozhnie quarry							Yavoriv quarry						
		T5	T6	E1	E2	E3	ZH4	ZH7	T5	T6	E3	E4	E7	ZH1	ZH2
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Department *Zygomycota*															
1.	*Absidia glauca* Hagem	0	0	12.3	6.0	9.6	12.0	0.3	0	0	0.5	1.5	2.2	0.5	0
2.	*Absidiablakesleana* Lendr.	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0
3.	*Zygorrhinchus moelleri* Vuill.	0	0	0.5	0	0	2.0	3.1	0	0	0	0.5	0	2.0	0
4.	*Mortierella alpine* Peyronel	0	0	7.5	0	9.6	0	2.5	0	0	1.5	2.5	0	3.1	4.8
5.	*Mortierella elongate* Linnemann	0	0	0	0	0	0	0	0	0	0	11.7	0	6.0	2.5
6.	*Mortierella* sp.	0	0	2.0	0	0	2.1	3.4	0	0	1.2	0	0	0.5	0
7.	*Mucor racemosus* Fresenius	11.2	0	0	0.5	4.8	1.5	2.1	0	0	0	0	0	0	0
8.	*Mucor globosus* Fischer	0	0	0	0	0	0.5	1.5	0	0	0	0	0	0	0
9.	*Mucor hiemalis* Wehmer	13.5	29.0	0.5	1.7	1.5	6.5	9.6	17.5	15.7	20.0	11.7	0.5	6.5	9.6
10.	*Mortierella ramanniana var. angulispora (*Naumov*)* Linnem	30.3	40.0	35.5	40.0	30.0	15.7	13.5	50.6	30.0	30.0	17.9	55.0	13.5	15.7
11.	*Rhizopus nigricans* Fhrenb.	30.0	35.5	24.5	9.6	13.5	0	0	45.0	15.7	9.6	24.5	35.0	17.9	0.5
12.	*Rhizopus oryzae* Went et Prin. Geerligs	0	0	0	0	0	9.6	0	0	0	2.5	1.5	0	0	13.5
Department *Ascomycota* light colored															
13.	*Aspergillus terreus* Thom	0	0	13.5	20.0	25.7	15.7	13.5	0	0	20.0	17.9	15.7	12.8	0
14.	*A. ustus* Bainier	0	0	0	0	9.6	6.5	0	0	0	0	2.5	13.5	9.6	4.8
15.	*A. niger v.*Tieghem	23.5	25.5	20.0	17.9	13.5	15.7	9.6	40.5	20.9	20.5	9.6	52.5	9.6	13.5
12.	*A. fumigatus*Fres.	35.5	20.5	20.0	17.9	20.0	40.9	35.5	30.5	20.0	30.5	13.5	47.5	15.7	13.5
13.	*A. repens* (Cda.) Sacc.	0	0	13.5	15.7	9.6	13.5	15.7	0	0	17.9	13.5	0.7	20.0	17.9
14.	*A. ochraceus* Wilhelm	0	0	9.6	3.5	15.7	17.9	13.5	0	0	3.5	9.6	6.5	3.5	15.7
15.	*A. gracilis* Bainier	0	0	0	0	1.5	0.4	0	0	0	0	0	0	0.8	0.4
16.	*A. versicolor* (Vuill)Tiraboschil	0	0	0	0	1.5	0	0	0	0	0	0	0	1.2	0
17.	*A. flavus*Link.	0	0	0	0	0.8	0.4	0	0	0	0	0	0	0.5	0.4
18.	*A. wentii* Wehmer	0	0	0	0.4	0	0.4	0	0	0	0	0	0	0	1.2
19.	*A. alliaceus* Thom et Church	0	0	0	0	1.2	0	0	0	0.4	0	0	0	0	0.5
20.	*A. flavipes*(Bain et Sart.) Thom et Church	0	0	0	0.5	0	0.5	0	0	0	0	0	0	1.5	0
21.	*Acremonium strictum* Gark	0	0	3.5	0	0.8	1.2	0.4	0	0	0.4	0.4	0.2	0	1.5
22.	*Acremonium murorum* (Corda) Gams	0	0	0	0	0	0	1.5	0	0	0	0	0	0	0.5
23.	*Cylindrocarpon destructans* (Kins)	0	0	0	0	0	0.5	1.2	0	0	0	0	0	0	0
24.	*Chaetomium spirale* Zopt	0	0	0	0	0	1.2	1.5	0	0	0	0	0	0	0
25.	*Gliocladium Zaleski* Pidopl.	0	0	0	0.5	0	0	0	0	0	0	1.2	0	0	0
26.	*Stysanus microspores* Sacc.	0	0	0	0	0.8	0	0	0	0	4.2	0	0	0	0
27.	*Botriotrichum piluliferum* Sacc. et March.	0	0	0	0	0	0.4	1.5	0	0	0	0	0	0	0.5
28.	*Verticillium album* (Preuss) Pidopl.	0	0	0	10.0	0	0	0	0	0	0	0	0	0	0
29.	*Fusarium oxysporum* Schlecht	22.7	25.6	25.7	15.5	30.5	25.5	30.9	52.7	30.5	20.0	24.7	48.0	17.9	15.7
30.	*F. culmorum*	0	0	4.5	0	9.6	13.5	4.5	0	0	3.5	1.7	0	1.7	9.6
31.	*F. moniliforme* Scheld	10.0	9.6	20.0	13.5	0	15.7	25.5	17.5	9.6	13.5	17.9	0	24.5	10.0
32.	*F. solani* (Mart) App.et Wr.	0	0	0	0	0	0	0	0	0	13.5	9.6	10.0	4.5	9.6
33.	*F. lateritium* Nees	0	0	0	1.7	0	0.4	0	0	0	1.5	0	0	0.5	0
34.	*F. avenaceum*(Fr) Sacc.	0	0	0	0	0	0	1.7	0	0	0	0	0	0	0
35.	*F. semitectum* berk.et Rav.	0	0	0	0	4.5	0	0	0	0	0	0	0	0	1.3
36.	*F. graminearum* Schwabe	0	0	1.5	0	0	0	0	0	0	0	0	0	0	0

Table 5. Cont. Species composition of micromycetes and its frequency (%) in the soils of Yavoriv and Podorozhnie sulfur quarries

37.	*F. javanicum* Koord.	0	0	0	0	0.4	0	1.5	0	0	0	1.5	0	0.5	0
38.	*Metarrizium anisopliae* (Metsch) Sorokin	0	0	0	0	0	1.5	0	0	0	0	0	0	0	0
39.	*Paecilomyces* sp.	12.0	17.9	13.5	9.7	4.5	1.7	9.6	25.5	17.9	10.0	9.6	25.5	9.6	1.5
40.	*Paecilomyces* lilacinum (Thom) Samson	32.4	30.0	20.5	25.5	10.5	20.0	17.9	55.7	48.5	35.5	30.5	55.7	20.0	15.7
41.	*Penicillium roseopurpureum* Dierck	24.2	18.7	25.5	30.5	20.0	0	0	57.9	15.7	17.9	20.0	55.5	0	0
42.	*P. waksmanii* Zaleski	20.5	20.5	20.0	17.9	20.0	0	0	52.4	20.0	20.0	17.9	48.5	0	0
43.	*P. nigricans* (Bainier) Thom	18.5	30.5	20.5	17.9	20.5	17.9	15.7	53.5	20.5	17.9	20.0	45.7	9.6	10.0
44.	*P. funiculosum* Thom	22.4	20.0	15.7	10.0	9.4	0	1.5	35.7	20.5	17.9	7.5	21.5	0	0
45.	*P. crustozum* Thom	0	0	25.5	20.0	17.9	10.0	9.4	0	0	12.3	11.8	2.0	25.4	20.0
46.	*P. brevi-compactum* Dierckx	0	0	20.8	25.5	15.7	20.0	17.9	0	0	12.5	9.7	1.5	20.0	17.9
47.	*P. chryzogenum* Thom	0	0	0	12.7	9.8	5.4	1.7	0	0	1.7	0	0	12.7	17.5
48.	*P. ochro-chloron* Biourde	0	0	20.7	30.5	20.5	12.7	20.5	0	0	15.7	15.7	0	9.6	12.5
49.	*P. lilacinum* Thom	0	0	15.7	20.0	17.5	15.7	10.0	0	0	9.6	1.5	4.3	20.5	10.7
50.	*P. citrinum* Thom	0	0	4.7	1.5	10.0	9.7	0.4	0	0	0.4	0	0	17.5	10.0
51.	*P. spinulosum* Thom	0	0	0.4	1.5	0.8	0.4	1.5	0	0	12.5	10.0	0.4	1.5	1.7
52.	*P. lividum* Westl.	0	0	10.0	20.5	17.3	9.7	4.0	0	0	10.0	12.7	0.4	12.5	0.4
53.	*P. rubrum* Stoll	0	0	15.7	9.4	5.7	0.4	12.5	0	0	10.0	13.7	0.4	17.9	20.5
54.	*P. raciborskii* Zaleski	0	0	0	0	0	0.5	0.4	0	0	1.5	0.8	1.5	12.5	8.7
55.	*P. luteum* Zukal	0	0	0	1.5	0	5.7	0.5	0	0	2.4	3.7	0	17.5	15.7
56.	*P. citrinum* Thom	0	0	0	7.8	0	0	0	0	0	0	0	0	0	0
57.	*Trichotecium* rozeum Lk.	0	0.5	0.8	1.5	7.8	3.7	12.5	0	9.7	12.5	0.5	0.4	12.7	10.5
58.	*Trichocladium asperum* Harz	0	0	0	0	0	0	0	0	0	15.7	0.5	0.5	10.5	12.7
59.	*Pestalotia hartigii* Tubent	0	0	0	0	0	0	0	0	0	0	1.5	0.2	12.7	10.0
60.	*Trichoderma viride* (Pers. Et S.F. Gray.)	25.7	20.5	35.7	30.8	35.5	37.8	40.7	55.2	35.7	30.5	28.5	48.2	25.5	20.0
61.	*T. lignorum* (Todle) Has.	0	0	10.0	7.5	9.7	10.5	15.7	0	0	15.7	12.5	0.2	2.0	7.5
62.	*T. harcianum* Rifal	20.5	0	17.9	15.7	10.5	9.7	5.2	10.5	0	0	10.5	1.2	12.7	10.0
	Department *Ascomycota* dark colored														
63.	*Aureobasidium pululans* (de Bary) Arnaud	17.9	25.5	20.0	30.8	27.5	20.5	25.5	38.5	25.8	30.0	25.5	48.7	25.5	17.5
64.	*Alternaria alternate* (Fr.) Keissler	0	20.8	25.5	20.0	30.5	17.5	20.0	0	0	30.5	0	0	12.5	10.0
65.	*Cladosporium cladosporioides* (Fres.) de Vries	17.5	20.0	12.7	38.5	20.0	17.5	15.7	48.5	20.8	25.5	20.0	50.0	20.0	17.9
66.	*C. herbarum* (Pers.) Link ex Gray	25.5	20.5	30.7	35.5	25.5	20.0	17.9	52.5	35.5	20.7	10.5	50.0	17.5	15.0
67.	*C. brevi-compactum* Pidopl. et Deniak	0	0	0	12.7	0	0	0	0	0	0	0	0	0	0
68.	*Humicola grisea* Traaen	20.0	17.9	20.5	0	15.7	20.0	12.5	48.9	25.5	20.0	17.9	50.0	12.5	10.0
69.	*Oidiodendron echinulatum* Barron	10.5	0	7.8	12.5	0	0	0	55.7	35.5	35.7	30.5	30.0	0	0
70.	*Ulocladium consortiale* (Thum) Simmons	25.5	20.5	17.8	35.5	15.7	20.0	17.5	47.5	20.0	25.7	30.5	50.0	0	0
71.	*Torula herbarum* (Pers.) Link	0	0	10.0	0	0	0.4	0.8	0	0	9.7	1.5	15.7	10.0	9.7
72.	*Phoma pomorum* Thum.	0	0	12.5	10.0	7.5	7.2	5.0	0	0	0.5	1.2	0	0.4	0.5
73.	*Phoma glomerata* (Corda) Wr. et Hochap.	0.5	0	0.7	2.5	0	0.4	0.5	0.5	0	0	0	1.5	0.4	0.2
74.	*Phoma sp.*	0	0	12.5	17.5	4.5	3.2	1.7	0	0	0	0	0.4	10.0	9.6
75.	*Mycelia sterilia* (white)	20.8	25.7	5.5	0	0	0	0	50.0	18.5	0	0	45.7	0	0
76.	*Mycelia sterilia* (darc)	24.3	20.0	0	0	0	0	0	58.4	20.0	0	0	45.5	0	0

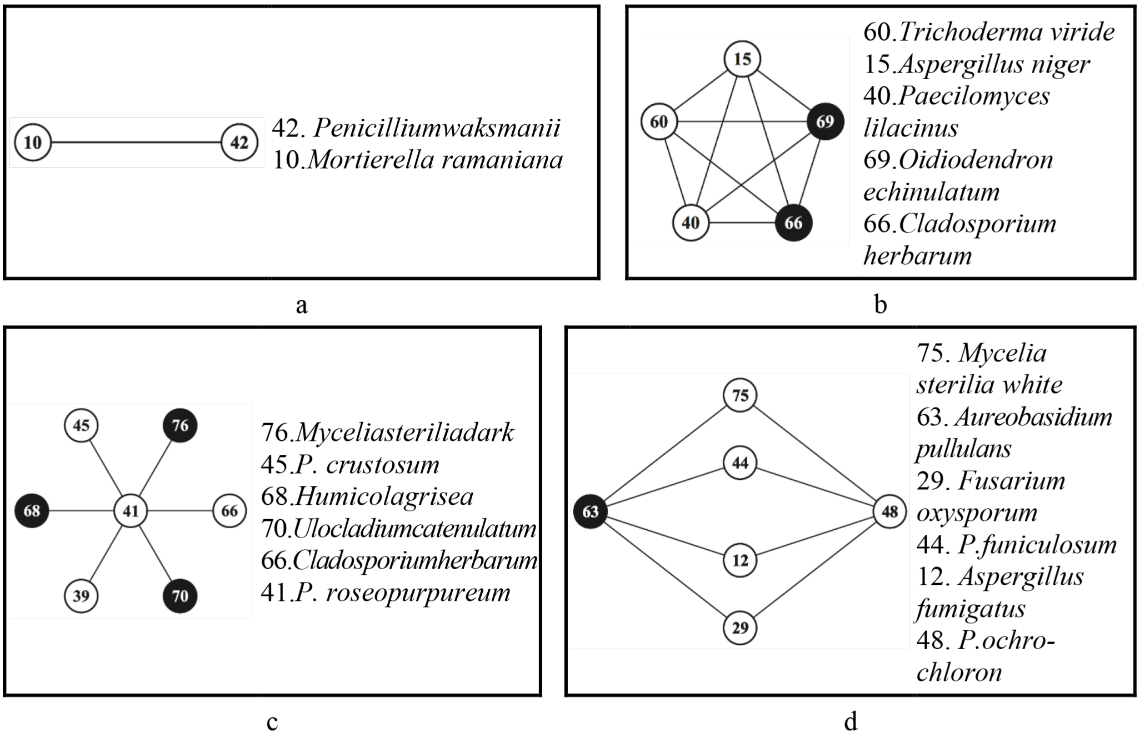

Figure 2. Correlation groups of fungal communities of the Yavoriv sulfur quarry (a, b – SO_4^{-2} 8.0-7.5; c, d – SO_4^{-2} 44-50 in the soil solution)

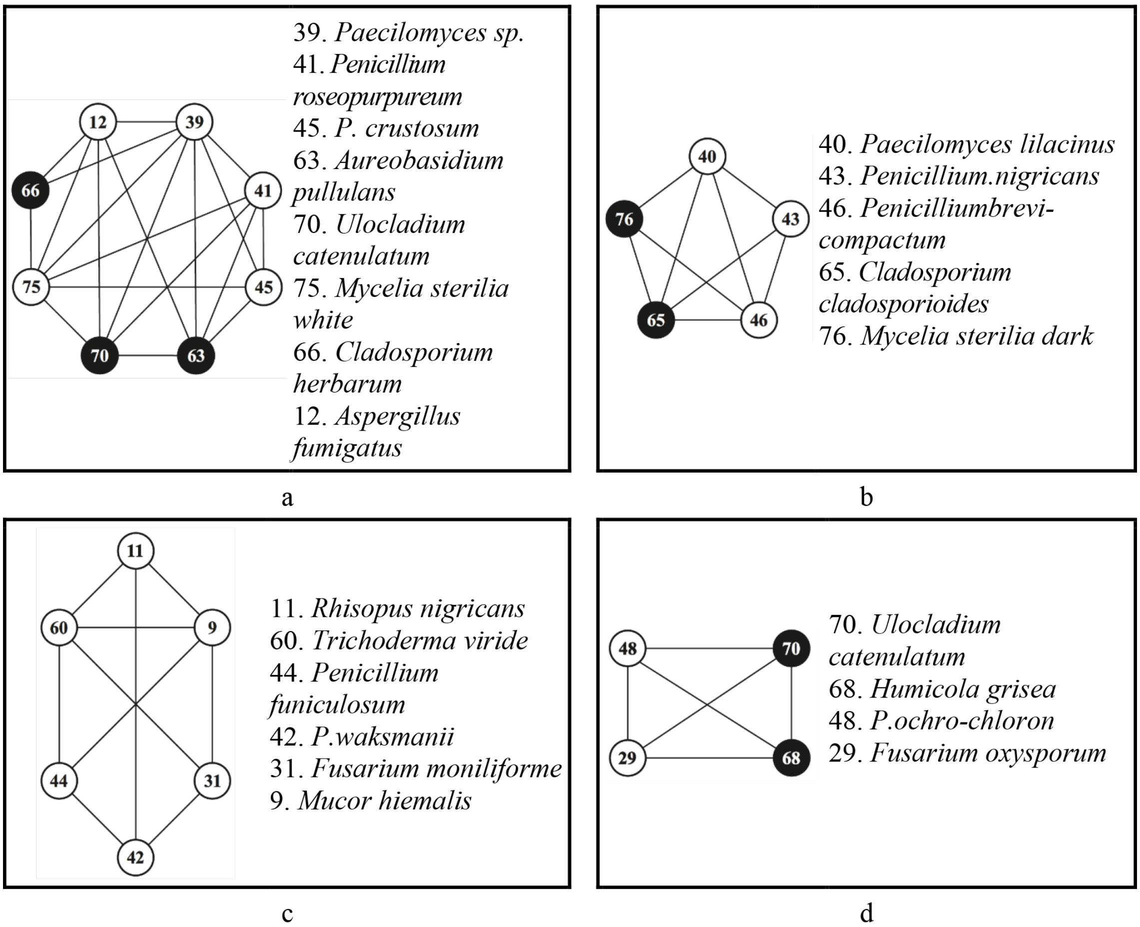

Figure 3. Correlation groups of fungal communities of the Podorozhnie sulfur quarry(a, b – SO_4^{-2} 4.0-4.4; c, d – SO_4^{-2} 9.5-10 in soil solution)

In places of increased anthropogenic load, the study of micromycetes is determined by the importance of identifying indicator species for technogenic pollution.

According to the results of the correlation analysis, in the soils of the Yavoriv sulfur quarry compound complexes of soil micromycetes were formed based on the content of SO_4^{-2} in the soil solution, which exceeded the background concentration in 44-50 times. Light-colored species of the genera *Penicillium* and *Aspergillus*, as well as melanin-containing deuteromycetes of the genera *Cladosporium, Ulocladium, Humicola,* and *Aureobasidium* were structural. In the territories where the content of SO_4^{-2} in the soil solution exceeded the background concentration in 7.5-8 times, the correlated groups had linear structures, they were either formed or were in a state of decay. Among the complex were the six-membered and seven-membered groups, where *Cladosporium herbarum, Ulocladium catenulatum, Humicola grisea, Aureobasidium pullulans* were among the melanin-containing species (Figure 2).

The correlation groupswhich formed at the Podorozhnie sulfur quarry, where the SO_4^{-2} content in the soil solution exceeded background concentrations by 9.5-10 times, were four- and six-membered complexly organized structures. Structural genera in the groupswere species of the genera *Penicillium, Fusarium, Rhisopus, Mucor, Tichoderma, Ulocladium, Humicola.* The eight-membered structures in soils where the content of SO_4^{-2} in the soil solution exceeded background concentrations by 4.0-4.4 times turned out to be the most complexly organized. They were connected by strong trophic ties and formed structures from species of the genera *Penicillium, Aspergillus, Cladosporium, Ulocladium, Paecilomyces,* and the structural genera included *Mycelia sterilia (white)* and *Mycelia sterilia (dark)* (Figure 3).

It should be noted that the development of the species *Tichoderma viride,* which is a positive ecological factor for devastated soils, was especially active in all periods of the year. *Tichoderma viride* is used as a seed treatment and applied directly to the soil to control pathogen levels. The fungicidal effect of *Tichoderma viride* is used in biological control against phytopathogenic fungi, such as *Rhizoctonia, Pythium, Fusarium, Macrophomina phaseolina* and a number of wood-destroying fungi, in particular powdery mildew.

Ecological indices and statistical indicators

Species diversity of micromycete complexes is characterized on the basis of indices of diversity and evenness adopted in general ecology, which represent a mathematical expression of the relationship between the number of species and their quantity. The results of the calculations are summarized in Table 6.

The value of indicators of the structure of microscopic fungal complexes for both types of soils indicates significant differences between zonal soils and soils disturbed by sulfur mining. The index of species diversity in zonal soils is higher. This testifies to the stability of the structure of microscopic fungal communities of the studied territories.

Similarly, the Shannon, Simpson, and Peasloo indices are higher on soils of zonal types. The maximum values of indicators of species diversity were recorded in 2021, which confirms the self-regenerating functions of the quarry, self-regrowth and restoration of natural communities.

Taking into account the indicators (diversity index and dominance index), the following types of plots were selected:

- low values of diversity indices, leveled structure of dominance – areas of embryozems;
- low values of diversity indices, clearly defined dominant species – areas of embryozems;

Table 6. Indices of ecological diversity of soil micromycete communities of soil monitoring plots of the Yavoriv Sulfur Quarry

Variants	Season	Index of species diversity Sorensen	Simpson Dominance Index	Index Shannon	Index Peasloo
Embriozems	2011	9.34	0.011	1.02	0.38
	2016	9.47	0.014	1.03	0.34
	2021	11.24	0.102	2.37	0.73
Zonal soils	2011	13.56	0.087	2.76	0.79
	2016	16.64	0.066	3.07	0.79
	2021	16.91	0.068	3.12	0.84

- high values of diversity indices, leveled structure of dominance, more uniform distribution – zonal soils.

CONCLUSIONS

The species composition and taxonomic characteristics of soil micromycetes of forest ecosystems disturbed by sulfur mining were studied. It was found that on the territories where the natural regeneration of vegetation occurs after the extraction of sulfur the processes of restoration of phytocenoses take a very long time. It should also be noted that the slight decrease in SO_4^{-2} content occurs in soils over the years, which could be determined by the increase in the biodiversity of soil micromycetes and the enrichment of the phytocenotic cover (Table 5). Therefore, the processes of natural restoration of devastated soils and reduction of the level of sulfur pollution occur very gradually.

Soil micromycetes, which form strong six-membered structures from K-strategistsin climactic ecosystems, completely change their structure in the extreme ecotopes of quarries, and the structural genera in correlation groups are L-strategiststhere. Bioindicator species for the excess of SO_4^{-2} ions and other xenobiotics in the soil solution were established. These species are *Mortierella ramanniana var. angulispora, Penicillium roseopurpureum, P. waksmanii, P. nigricans, P. funiculosum, Trichoderma viride, Cladosporium cladosporioides. C. herbarum, Aureobasidium pullulans, Humicola grisea, Ulocladium consortiale, Alternaria alternate Paecilomyceslilacinum, Fusarium oxysporum.*

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