JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2022, 23(11), 101–108
https://doi.org/10.12911/22998993/153399
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Received: 2022.08.07
Accepted: 2022.09.14
Published: 2022.10.01

Peculiarities of the Primary Process of the Soil Formation on the Mine Rock Dumps under the Influence of Biotic Factors

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ABSTRACT

Open pit coal mining is a global problem, because mines occupy large areas that completely change the relief, dramatically affect ecosystems, as a result of which they lose most of their functions, and a significant part of the fertile soil degrades and becomes unsuitable for agricultural activities. In the presented work, the initial stage of soil formation was studied, the parameters of the granulometric composition of uneven-aged rocks of Donbas mine dumps, their nutritional regime, and the species composition of soil algae were studied. Samples were taken from three different-aged rock dumps of the mines: "South-Donbaska - 3" (rock storage for 40 years); "South-Donbaska - 1" (storage of rock for 52 years), "Trudovska №5 - bis (storage of rock for more than 100 years). The agrochemical parameters of the rock were determined in the samples: pH_{water}, humus, nitrate nitrogen, mobile phosphorus, exchangeable potassium, particle size distribution. The determination of granulometric fractions of 0–20 cm layer of rock dumps of the mines shows, along with the age, a potential increase of the dump of fine fractions and a decrease in the fraction of stones from 83% in the dump of the South-Donbaska mine, and by 30 to 64.7% in the dump of the Trudovska No. 5-bis. The proportion of the clay fraction is not high in all dumps and it does not exceed 1%, but its appearance indicates the initial stage of a soil structure formation. Soil formation begins with the colonization of mineral rocks with soil algae. The species composition of soil algae, the quantitative accounting were determined by microscopy of a freshly selected soil sample and by cultural methods. Algae species were determined by determinants. In the rock dump, the structure of algal groups becomes more similar to, their structure in the background soils of the territory. The dominance of the representatives of Chlorophyta and Cyanophyta in the rock indicates the steppe process of soil formation. The data obtained contribute to the expansion of the ecological and biological understanding of the initial stages of the formation of soil cenoses.

Keywords: agrochemical indicators, algoflora, waste heaps, granulometric fractions, successions, soil formation.

INTRODUCTION

The first historical document about the discovery of hard coal in the Donbass is an entry in the journal of the Berg Collegium dated to 1723, which records the study of the samples near Bakhmut [Gayko et al., 2009]. For over 300 years it has been the largest industrial center of Ukraine. Its total area is 60 thousand km^2. Therefore, the coal industry of Ukraine has a powerful technogenic impact on the environment [Small mining encyclopedia, 2004].

The territory of the Ukrainian Donbass has about 1134 rock dumps. Over 8 billion tons of rock have been accumulated in these dumps and waste heaps [Zubova et al., 2012]. And they are located on 5000 hectares of land, which is 0.2% of the total territory of the region. On the surface

of waste heaps, under the influence of an unfavorable water regime, the toxic effect of sulfide-containing rocks, strong heating of the slopes of insolated exposures, and a harsh wind regime, the process of vegetation self-restoration (succession) is greatly extended in time (Kupriyanov et al., 2006). The volume of pollutant emissions from natural dumps is about 70 thousand tons per year. 10 tons of carbon oxides, 1.5 tons of sulfur dioxide and a significant amount of gaseous substances are released from the waste heap per day, since all dumps contain FeS_2 [Lisiecki et al., 2007; Sonko et al., 2018].

The availability of the large areas of recultivated lands which had emerged over the past decades in the mining area determined the relevance of studying the rates and mechanisms of the overgrowing of technogenic rock dumps. The regularities of soil formation from rock and ecosystems in the extreme conditions of the technogenic landscapes, the restoration of geosystems aimed at preventing the environmental impact on adjacent lands remain to be poorly studied scientific problems on a global scale [Sokolov et al., 2015; Sonko et al., 2021].

The main factors limiting the possibility of biological development of dumps are acidity or alkalinity, granulometric composition, nutrient content, humidity. During dumping, either dense silty, almost impermeable clays, or infertile quartz sands, as well as the rocks with a high content of pyrite, the oxidation products of which cause a highly acidic environment (pH = 2.0–3.5), are brought to the surface [Tomakov, 1994]. One of the initial stages of rock transformation, in particular, rock dumps of coal mines onto the soil, is the process of weathering and colonization with soil algae [Shushueva, 1988, Buligin et al., 2020]. Algae are an important factor in the transformation of sterile rocks into primary soil, preparing the conditions for nitrogen-fixing and heterotrophic microorganisms, as well as for the settlement of higher plants. In addition, soil algae are involved in the breakdown of some organic and mineral compounds, the excretion of mucous substances, the loosening of the upper soil layers and the formation of soil aggregates [Striganova, 1980; Karpenko et al., 2021].

The study of the processes that take place during the natural restoration of soil formation is not only an urgent fundamental task in soil science, but also makes it possible to predict the consequences of the application of reclamation measures when creating zones that are safe for humans and the environment [Sokolov et al., 2015; Kravchenko et. al., 2022].

In the environment, the research on algae is mainly associated with the pollution of water basins. Soil algae are studied less frequently, despite their significant role in the biological weathering of rocks and minerals and the formation of the upper soil layer. In addition, they successfully propagate on sandy soils in the water-deficient regions [Rahmonov et al., 2010]. As noted by S.F. Negrutsky, the soil formation begins with the settlement and development of algae [Negrutsky, 1990; Moklyachuk et al., 2015; Parfeniuk et al., 2015]. Soil algae are involved in soil protection from water and wind erosion due to the formation of a crust on the soil surface (West, 1990), in the regulation of water exchange [Eldridge, 2003],in the accumulation of organic matter, and also in the cycle of elements, which determines their important ecological significance in development of bare substrates [Schulz et al., 2016; Borchhardt et al., 2017], they increase the content of nitrogen available to ecosystems [Jayne et al., 1994; Evans et al., 2003]. The role of algae is especially significant in the regions with highly degraded soils as a result of mining. Algae, associated with the rhizosphere of microorganisms, plant roots and symbiotic fungi, stimulate soil formation.

Soil algae cannot regulate their water balance independently and they live on natural precipitation [Chubuk, 2005]. They withstand not only prolonged dehydration, but also temperature fluctuations from -79°C to +115°C, high solar activity and ultraviolet irradiation [Jainendra et al., 2019; Lingui Xue et al., 2005]. This allows them to be one of the hardiest organisms inhabiting the rock dumps of the coal mines, and makes it possible to use them in the phyto-recultivation of the waste heaps.

MATERIALS AND METHODS

The study the area under study of Donbass is located in the south-east of Ukraine. The climate is continental with pronounced dry winds [Buchinsky, 1963]. The annual amount of precipitation is minimal in the south and it amounts to 400–420 mm. In the Donetsk ridge, the amount of precipitation increases to 540 mm. The species composition of soil algae was studied in the samples of three different-aged rock dumps

of the mines: ”South-Donbass - 3” (rock storage for 40 years); ”South-Donbass - 1” (storage of rock for 52 years), ”Trudovska” No. 5 - bis (storage for more than 100 years).

The species composition of soil algae, the quantitative accounting were determined by: microscopy of a freshly selected soil sample and cultural methods, of which preference was given to plate cultures with fouling glasses on Bold's agar medium. Algae species were identified by determinants [Andreeva, 1998; Kostikov et al., 2001;Kondratieva, 1968;Kondratieva et al., 1984; Matvienko and Dokhadina, 1978; Moshkova and Gollerbakh, 1986; Prikhodkova, 1992].The following agrochemical parameters of the rock were determined: water pH – SSTU 26483-85; humus – SSTU 26213-91; nitrate nitrogen – SSTU 4729; mobile phosphorus, exchangeable potassium – SSTU 4115-2002; particle size distribution – SSTU 4730: 2007.

The dumps of Donbass coal mines consist of fragments of shale and sandstone of the Middle, Lower and Upper Carbon. They contain a significant amount of combustible substances (up to 34%), such as coal, carbonaceous substances in the rock, coal dust, sulfur and its compounds (Small mining encyclopedia, 2004). The lithological composition of carbon includes mudstones (argillaceous shale, which in the process of modern weathering turn into thinly platy fragments, and then into clayey mass), siltstones (sandy shales), sandstones, limestones, coal [Zubov, 2019].

Statistical analysis

Results were statistically evaluated by the analysis of variance. All the assays were carried out in triplicate, sand results were expressed as mean ±SD. All the calculations were made with help of Microsoft Office 2019 software package (Microsoft) [France and Thornley, 1984].

RESULTS AND DISCUSSION

The formation of edaphic conditions on the dumps of the coal mines begins with the intense oxidation of rock, coal, carbonaceous substances, which is the chemical weathering of the rock. These are the processes of oxidation, dissolution, the transfer of products of these processes, the formation of new granulometric elements [Jainendra et al., 2019]. It is known that the soil enriched with fine particles is considered to be potentially fertile (Medvedev and Laktionova, 2011). An analysis of the distribution of granulometric fractions in a layer of 0–20 cm shows, as the age grows, a potential increase of the dump, fine fractions and a decrease in the fraction of stones from 83% in the dump of the South-Donbass - 3 mine to 64.7% in the dump of the Trudovska mine (Fig. 1).

The medium dust fraction increases especially in the dumps of the older mine, increasing the water-holding capacity of these soils. The fine dust fraction and the silt fraction contain organic substances, have the ability to coagulate, to form structures and to have other positive properties, which in future will make it possible to use phyto-recultivation techniques on dumps [Medvedev and Laktionova, 2011]. The proportion of the silty fraction is not high, in all dumps it does not exceed 1%, but its appearance in the rock begins the process of structure formation. The content of easily hydrolyzed nitrogen compounds and mobile phosphorus in the rock dumps of all the studied mines is very low, the content of exchangeable potassium is low (Table 1). But with the increase of the storage age, the content of these elements tends to increase. The presence of humus in the rock dumps indicates the beginning of the soil formation process [Shtina et al., 1978].

Soil algae develop best in a neutral, slightly acidic or slightly alkaline environment/medium. In the soils of the Steppe of Ukraine, surface films of blue-green algae, resistant to drying and strong insolation, develop. Chestnut soils and solonetzes are characterized by the development of the nostoc-cytone complex and diatoms [Olkhovych et al., 2022]. 36 species of algae were identified on the surface of the studied dumps from 5 divisions (*Eustigmatophyta, Chlorophyta, Cyanophyta, Xanthophyta, Bacillariophyta*), from 7 classes (*Chlorophyceae, Eustigmatophyceae, Charophyceae, Cyanophyceae, Bacillariales, Bacillariophyceae, Xanthophyceae*), 13 orders *(Achnanthales, Chlorococcales, Volvocales, Protosiphonales, Scenedesmales, Trebouxiales, Klebsormidiales, Chlorellales, Eustigmales, Oscillatoriales, Nostocales, Mischococcales, Bacillariales)*.

Algae from the division *Chlorophyta* – 18 species and *Xantophyta* – 8 species are the most widely represented ones on the studied rock dumps. They make up 50.0% and 22.2% of the total number of species (Fig. 2). Green algae cenoses develop on relatively young dumps,

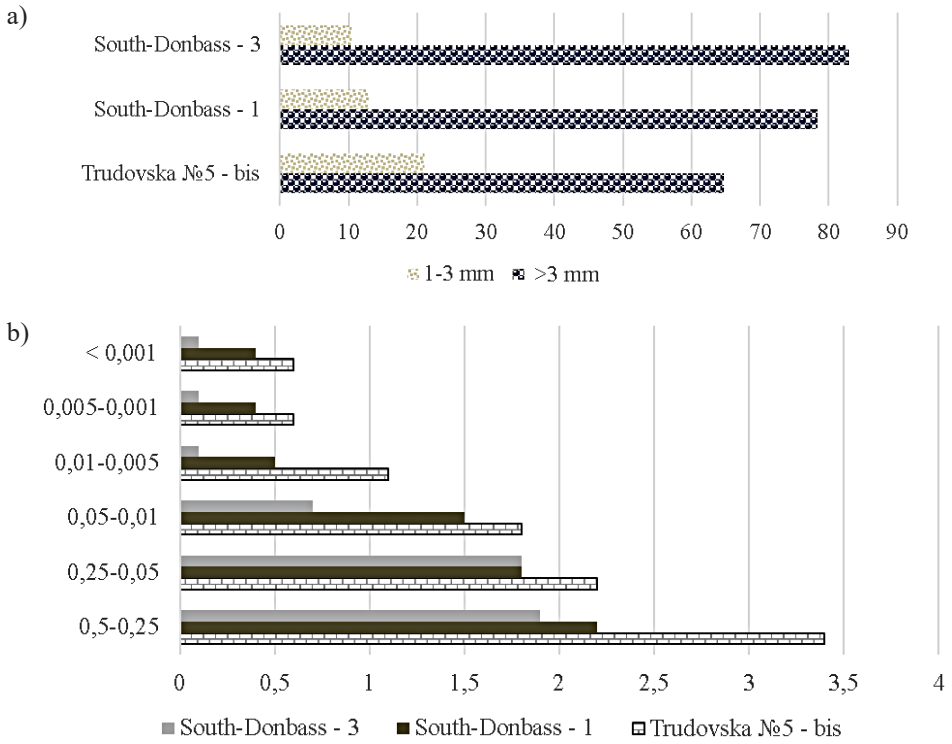

Figure 1. Distribution of the elements of granulometric composition of rocks of the mine coal dumps in a layer of 0–20 cm, % (A – particles of the skeleton, B – particles of a fine soil fraction)

Table 1. Agrochemical characteristics of the dump rocks in the 0–20 cm layer

Mine dumps	pH_{H_2O}	Humus, %	NO_3	P_2O_5	K_2O
			mg/kg		
Trudovska №5 – bis	5.6-6.9	1.2	0.30	2.5	26
South-Donbass – 1	4.60-6.75	0.6	0.16	1.6	23
South-Donbass – 3	4.41-5.33	0.4	0.1	1.4	18

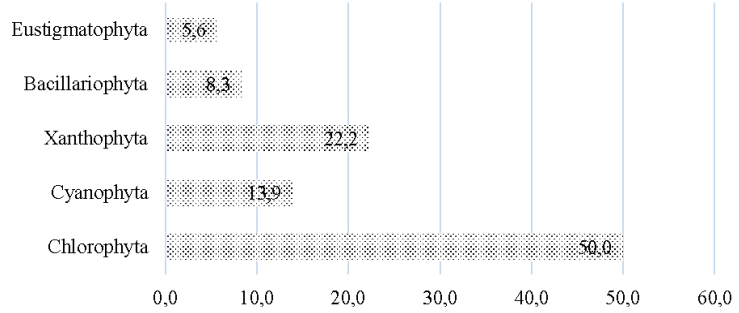

Figure 2. The total ratio of the number of species of soil algae in rock dumps of Donbass coal mines

later they are replenished with yellow-green, diatoms and blue-green algae [Kabirov and Gaisina, 2009]. The overgrowing of the deposit dumps occurs according to the type of primary successions. Diatoms are a source of detritus and a soluble organic matter [Shtina and Hollerbach, 1976]. The analysis of the species composition of soil algae in the studied rock dumps of the coal mines makes it possible to determine the features of their overgrowth.

Algae from the division *Chlorophyta* are represented by 11 species (45.8% of the total number of species) on the rock dump „Trudovska No. 5-bis, *Cyanophyta* division – by 5 species (20.8%) (Fig. 3a). On the studied rock dumps, algae from the division *Eustigmatophyta* are represented in a

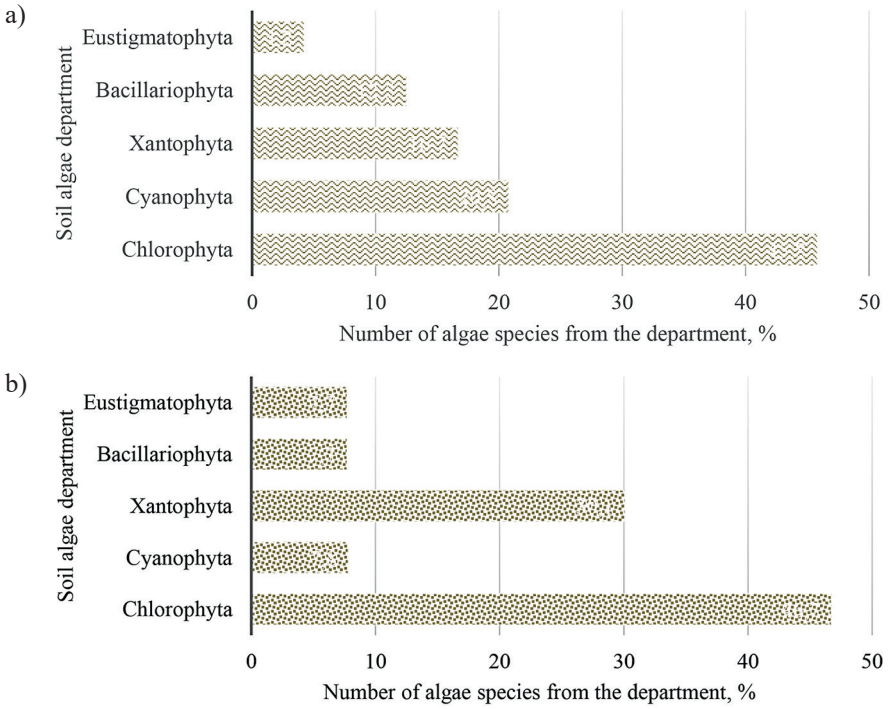

Figure 3. The structure of the algoflora (a) on the rock dump „Trudovska № 5-bis, (b) rock dumps of Donbass coal mines

smaller number – 1 species (4.1%), slightly more species of algae from the division *Bacillariophyta* – 3 (12.5%) and *Xanthophyta* – 4 (16.7%). On the rock dumps of the Yuzhno-Donbass 1 mine, the division *Chlorophyta* includes 6 (46.7%) species, *Cyanophyta* – 1 (7.7%) species, *Eustigmatophyta* and *Bacillariophyta* – 1 species each (7.7%), and *Xanthophyta* – 4 species (30.7%) (Fig. 3b). The surfaces of the dumps of the Yuzhno-Donbass 3 mine contain algae from the division *Chlorophyta* – 6 (55.0%) species, *Eustigmatophyta* and *Bacillariophyta* – 1 species each (9%), and *Xanthophyta* – 3 species (27%). On the studied rock dumps, the structure of algal groups gradually approaches the structure of background soils, where blue-green algae account for 50 species (39.1%), green algae – 40 (31.3%), yellow-green algae – 20 (15.6%), diatoms – 14 (10.9%), eustigmata – 4 (3.1%). The absence of blue-green algae in the dumps of the Yuzhno-Donbas-3 mine is probably due to the low pH level – 4.31–5.36.

The dominance of the representatives of *Chlorophyta* and *Cyanophyta* indicates the steppe process of the soil formation in the studied rock dumps [Chaika and Maltseva, 2013], that is, according to the regional pattern. These species are characterized by high resistance to adverse/unfavorable environmental conditions. Most of the found blue-green algae have slimy sheaths and involucres, which consist of hydrophilic colloidal polysaccharides and are able to quickly absorb and retain large amounts of water, which helps them withstand the fluctuations in the water regime of these soils. Species, which are highly resistant to various extreme conditions and which are identified as „ubiquitous" were also found in the studied substrates; they are first to appear even in a sterile mineral rock, do not have special morphological adaptations, but their protoplast, due to special physiological and biochemical features (high viscosity of protoplasm, a high concentration of cell sap and a relatively high content of bound water in the cell, a large suction force, etc.) provides them with drought resistance/guarantees their drought resistance [Prikhodkova, 1992].

The representatives of 6 families of microorganisms are the most common in the studied substrates, namely: *Phormidiaceae*, *Pleurochloridiaceae*, *Chlamydomonadaceae*, *Chlorococcaceae, Protosiphonaceae*, *Bracteacoccaceae*. The accumulation of biomass of microorganisms in the industrial dumps occurs in stages [Tarchevsky and Shtina, 1967]. At the first stage, groups of unicellular green and yellow-green ones are formed (mainly *Chlorella, Chlorococcum, Eustigmatos, Botrydiopsis* species), this stage corresponds to the aerophyton. At the second stage, nitrogen-fixing algae appear – *Nostoc* species, which are

Table 2. The influence of the weather conditions of the year and the age of the mine dumps on the formation of the number of the investigated microorganisms

Type of microorganism	Share of influence of the factor, %			
	Weather conditions of the year (A)	Age of mine dumps (B)	Interaction of factors (A+B)	Other factors
Chlorophyta	8	63	28	1
Cyanophyta	97	1	1	1
Xantophyta	33	13	52	1
Bacillariophyta	13	75	11	1
Eustigmatophyta	61	18	20	1

found only in the dumps of the Trudovska mine No. 5-bis. Sometimes *Phormidium* species develop simultaneously – this stage corresponds to epilithophyton – a grouping that plays an important role in the accumulation of organic matter and nitrogen on rocks. The third stage begins with the introduction of green threads into the cenosis and corresponds to the primitive edaphon. The settlement of green threads coincides with the settlement of higher plants on the dump [Safonova and Reva, 2009]. The overgrowing of waste heaps of coal mines with higher green plants occurs 30–40 years after filling. Green and yellow-green algae predominate in the dumps of the mines "South-Donbass-1" and "South-Donbass-3" under study. In the dumps of Trudovska mine No. 5-bis, the number of blue-green algae, although not predominant, has increased significantly due to a decrease in the proportion of yellow-green algae. The algoflora of the studied dumps is formed due to the introduction of diaspores and vegetative algae from the surrounding area and under the influence of zonal and geographical conditions.

With the self-development of microorganisms, algae groups, typical for these natural landscapes, gradually form on the dumps. The dumps are also characterized by a number of factors that are unfavorable for the life of many algae: low humidity (due to the low content of the physical clay fraction), strong insolation, and specific chemical composition. The development of algae precedes the settlement of higher plants and represents the primary stage in the scheme of synergy of vegetation on a purely mineral substrate.

The conducted dispersion analysis (Table 2) of the obtained long-term data has revealed that the formation of the number of microorganisms of the genus Chlorophyta is affected mostly by the age of mine dumps (63%), that of the genus Cyanophyta is affected mainly by the weather conditions of the year (97%), the number of microorganisms of the genus Xantophyta is mostly affected by the interaction of factors, the age of the dumps and weather conditions of the year (52%), that of the genus Bacillariophyta is affected mostly by the age of mine dumps (75%), the formation of the microorganism number of the genus Eustigmatophyta is affected significantly by weather conditions of the year (61%). It is possible to state that the studied factors have a serious impact on the development intensity of the microorganisms under study, and the former affect their development in different ways.

CONCLUSION

The determination of granulometric fractions of 0–20 cm layer of rock dumps of the studied mines shows a potential increase with age in the dump of fine fractions and a decrease in the stony fraction from 83% in the dump of the Yuzhno-Donbass - 3 mine to 64.7% in the dump of the Trudovska No. 5-bis mine. The silt fraction in all dumps is low and it does not exceed 1%, which indicates the beginning of the structure formation process. Green and yellow-green algae predominate in the dumps of the Yuzhno-Donbass-1 and Yuzhno-Donbass-3 mines. In the dumps of Trudovska mine No. 5-bis, the number of blue-green algae, although not predominant, has increased significantly due to a decrease in the proportion of yellow-green algae. The absence of blue-green algae in the dumps of the Yuzhno-Donbass 3 mine is probably associated with a low pH level of 4.31–5.36. The dominance of representatives of *Chlorophyta* and *Cyanophyta* indicates the steppe process of soil formation. They are characterized by high resistance to adverse/unfavorable conditions of the existence. The influence of the age of the mine dumps on the development intensity of the investigated microorganisms was revealed.

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