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Non-traditional fertilizers as soil ameliorants: the study of usefulness

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Abstract. The research studies the chemical, agrochemical, biological and toxicological impacts of non-traditional fertilizers (compost based on sewage sludge and the sawdust of hardwood and softwood trees) on soil and ecological conditions of a recultivated site (a sand quarry). It is indicated that it will be feasible to use non-traditional fertilizers with a 5-year composting period as an ameliorant for sandy soils.

1 Introduction

The reclamation of disturbed lands improves the environmental situation and ensures the reuse of these lands for different economic activities. When recultivating quarries for non-metallic building materials, including sand quarries, where topsoil is destroyed, it is important to use organic fertilizers to increase fertility. In this case, sewage sludge can be used as a source of organic matter.

There is a lot of experimental data on sewage sludge disposal [1–3]. However, it is worthwhile to study the feasibility of using sewage sludge and sludge-based composts on a regional level taking into account the differences in the chemical composition of sludge, soil and climatic conditions and even the type of anthropogenic transformation experienced by an ameliorated site. Thus, this issue is still important.

The use of sewage sludge in agriculture is limited because it contains heavy metals, pathogenic flora, etc. Some specialists believe it would be more appropriate to use sludge in forestry rather than agriculture [4–6]. However, even in forestry, the use of such ameliorants requires control.

This work assesses the safety of compost, based on sewage sludge for the environment.

2 Methods

The laboratory tests were carried out using the equipment of the Centre of ecology, biotechnology and clean fuels in the Volga State University of Technology.

Cellulose-digesting and proteolytic actions of soil were determined in field conditions by the application method [7]. The ammonifying action was evaluated in a laboratory, based on the technique developed by T.V. Aristovskaya [8].

Sample collection and preparation were done according to state standards [9]. Biotesting was carried out on three standardized test-organisms [10–12] and seeds of radish.

The population of micro-organisms was assessed by the swab method involving selective nutrient media. The total population of micro-organisms was defined based on Vinogradsky method, modified by Schulgina. The following types of agar were used to count the number of micro-organisms: meat-and-peptone agar for bacteria that assimilate the organic compounds of nitrogen; starch-and-ammonia agar for the population of micro-organisms that use mineral nitrogen; acidified wort-agar for micromycetes; soil agar for oligotrophic plants; nitrite agar for indigenous micro-organisms. Nitrite bacteria were counted based on Skerman agar medium, while cellulose digestors and azotobacter were calculated by the method of lump fouling in Hutchinson and Ashby medium [13].

The chemical analysis (atomic absorption method) was done according to ISO 11466 and ISO 11047 on AAnalit-400 atomic absorption spectrometer. [14]

The statistical assessment of obtained data was carried out with Statistica 6.0.

3 Results

Laboratory tests were used to analyze the content of heavy metals in non-traditional ameliorants, evaluate their levels of toxicity and determine their danger classes by means of biotesting.

The mobile forms of heavy metals can disturb the regulation of cell mechanisms and accumulate in plants. That’s why this indicator is important for new ameliorants. The content of heavy metals was determined in compost, based on sewage sludge and hardwood and softwood sawdust that didn’t reach the thermophilic state: Pb – 7.17 mg/kg; Cu – 16.99 mg/kg; Zn – 38.49 mg/kg ;Cd – 1.62 mg/kg; Ni – 8.78 mg/kg.

The biotesting of soil ameliorants was done with three test organisms (daphnia, chlorella, bacterium). The

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results have shown that the sensitivity of test organisms to the components of waste is different (table 1).

The biotesting of compost samples (sewage sludge + sawdust) taken at different stages of composting indicates that compost which didn't get through the thermophilic stage (a 3-year composting period) is more toxic: the analysis involving two test organisms showed IV class of hazard. The toxicity of compost after the thermophilic stage (a 5-year composting period) decreases: IV class of hazard was only for one organism (algae). The tests involving bacteria showed no toxicity of ameliorants. The values are distributed within the V hazard class.

As hazard class is determined based on the test organism that was the most sensitive to analyzed medium, the toxicity of both types of compost belongs to the IV hazard class (hypotoxicity).

Thus, the evaluation of non-traditional ameliorants based on sewage sludge showed their hypotoxicity, while the most sensitive test organism, in this case, is *Chlorellavulgaris* algae.

In field conditions, the evaluation of soil ameliorants was carried out on experimental plots in a sand quarry to be recultivated.

Most soils in the Mari El republic are sod-podzolic with low natural fertility. The research showed that the sand quarry soil has a low content of humus (0.72 %) which is only a half of humus content in new soils on adjacent territories. The amount of mobile phosphorus and exchangeable potassium is low: 1.2 mg/100 g and 1.7 mg/100 g of absolute dry soil correspondingly. The reaction of the medium is strongly acidic (pH=4.7). The quarry soil is heavily compacted in comparison with natural soils (1.7 times).

The content analysis of heavy metals in the quarry soil and adjacent forest territory didn't find the exceedance of tolerable levels. However, in forest soil, their concentration was higher than in the quarry (table 2). This is probably due to the lack of the most contaminated layer of soil in the quarry.

The evaluation of the biological activity of soil in the quarry showed no significant differences in terms of such parameters as ammonifying and proteasic activities as well as the increase in transformation of complex organic substances in the soil of the sand quarry in comparison with the natural territory (Table 3).

Biotesting involving three test organisms (daphnia, chlorella and radish) showed no toxicity in soil extracts both from natural territory (SDF=1; TDF=1; factor toxicity index (FTI)=1.02) and the sand quarry (SDF=1; TDF=1.51; FTI=0.99).

Table 1. The class of hazard for non-traditional ameliorants determined with biotesting methods involving daphnia, bacteria, and algae

The variants of the experiment	The toxicity indicators in case of daphnia			The toxicity indicators in case of bacteria		The toxicity indicators in case of algae		Hazard class
	Lethal dilution factor $(LDF)_{(50\text{-}48)}$	Safe dilution factor $(SDF)_{(10\text{-}48)}$	Hazard class	T-index of toxicity	Hazard class	Toxic dilution factor $(TDF)_{(+20/30\text{-}22)}$	Hazard class	
Fertilizers with a 5-year composting period	–	1	V	-1.13	V	6.03	IV	IV
Fertilizers with a 3-year composting period	4.68	10.8	IV	-13.56	V	8.13	IV	IV

Table 2. The content of heavy metals in the soils of studied sites

The variants of the experiment	The content of metals in soil, mg/kg				
	Cu	Cd	Zn	Sr	Pb
Natural territory (forest)	2.751±0.045	0.183±0.024	2.49±0.411	0±0.00	4.135±0.376
Sand quarry	1.27±0.021	0±0.00	2.37±0.142	0±0.00	0.72±0.022
Maximum permissible concentration	3.0	0.5	23.0	7.0	32.0

Table 3. The biological activity of soil at studied sites

The variants of the experiment	The biological activity of soil		
	Cellulose-digesting activity, %	Ammonifying activity, pH of air environment	Proteolytic activity, %
Natural territory (forest)	13.57	7.33	0.71
Sand quarry	27.67	6.67	0.51
LSD_{05}	3.35	-*	-*

*- the differences at the 5 % level of significance are not reliable

The changes in physical and agrochemical properties in anthropogenically transformed soil are obviously reflected in the structure of the microbial community (table 4).

The results of studying quantitative, trophic and taxonomic compositions of prokaryotic cells and mycelial organisms showed that the soil of the sand quarry contains the prevailing oligotrophic population of micro-organisms and decreased quantity of aerobiotic cellulose-digesting bacteria and mycelial fungi. The increase in pedotrophy and oligotrophic coefficients with equal mineralization of organic substances in soil indicates the activity of processes connected with humus and humus-bearing substances disposal.

Using criteria and indicators for soil degradation [15] allowed for making the conclusion about the extent of the sand quarry transformation: physical and chemical parameters show the fourth grade of soil degradation, while biological parameters don't differ much from the indicators of natural territory.

Table 4. The population of main ecological and trophic groups of micro-organisms and the indicators of activity of microbiological processes in podsolic sandy soil

Groups of micro-organisms and the indicators of activity of microbiological processes	Sand quarry	Natural territory (forest)
Ammonifiers, million CFU / gram of absolute dry soil	1.02±0.06	1.05±0.05*
Aminoautotrophs, million CFU / gram of absolute dry soil	0.48±0.02	0.49±0.02*
Actinomycetis, million CFU / gram of absolute dry soil	0.21±0.01	0.14±0.01
Oligotrophic plants, million CFU / gram of absolute dry soil	1.36±0.05	1.05±0.04
Humus destructors, million CFU / gram of absolute dry soil	0.92±0.03	0.21±0.01
Mycrommycetis, thousands CFU / gram of absolute dry soil	0.007±0.35	0.084±3.94
Cellulose destructors,**	40.0±1.16	54.0±1.83
Nitrogen fixers,**	14.0±0.71	0.0±0.0
Mineralization coefficient (meat-and-peptone agar/starch-and-ammonia agar)	0.47	0.47
Pedotrophy coefficient (soil agar/meat-and-peptone agar)	1.34	1.00
Oligotrophic coefficient (nitrite agar/meat-and-peptone agar)	0.90	0.21

* – the differences at the 5 % level of significance are not reliable;
** – % of soil lumps fouling

The soil of the sand quarry was fertilized with a non-traditional organic fertilizer (sewage sludge + sawdust) with a 5-year composting period (120 tones/ha) and the same non-traditional fertilizer but with a 3-year composting period (120 tones/ha).

When planning ameliorating activities, it is necessary to consider their influence on soil biota. The indicators of biological activity allow for identifying the direction of changes in soil and ecological conditions, soil fertility. This becomes obvious even earlier then changes in other fertility indicators happen (e.g. the content of humus). The most useful ameliorating techniques are identified as a result of the comparison. That’s why the field experiments first involved the determination of the actual biological activity of soil three months after the introduction of ameliorants.

The evaluation of the biological activity of soil on experimental sites showed that there were significant differences between experimental variants and control samples (excluding cellulose-digesting activity in the case of fertilizers with a 3-year composting period) (Table 5). The monitoring of changes in chemical, physical and biological parameters of soil and phytotoxicity was carried at the recultivated object for 8 years.

The agrochemical analysis shows that the degree to which main nutritional substances are available, as well as the content of humus in the soil at the site, are decreasing (Table 6). The content of humus is decreasing in all variants of the experiment in comparison with initial values. This is due to the activity of micro-organisms that started to use less available organic matter (humus) because the available ameliorants are lacking.

However, in comparison with control samples, the variants of the experiment indicate a better situation with humus and the availability of main nutritional substances. The exception is the variant involving fertilizers with a 3-year composting period. In this case, the content of potassium is 2 times lower than in the control sample. Also, the soil becomes less acidified in the variants of the experiment.

The introduction of non-traditional ameliorants doesn’t significantly impact the content of heavy metals in soil (Table 7) and their content doesn’t exceed the maximum permissible concentrations.

The study of the possible toxicity of soil at the experimental site which was carried out by biotesting for the whole period of research (2011–2016) showed low toxicity of soil ameliorated with compost having a 3-year composting period. Since 2015 the biotesting was performed only on radish seeds. The results have shown no phytotoxicity in all variants of the experiment and the state of bio-organisms is normal (FTI from 0.96 to 1.0).

The analysis of biological activity indicators has shown that involved ameliorants activate cellulose-digesting and ammonifying activities both in terms of fertilizers with 3 and 5-year composting periods (Table 8).

Table 5. The biological activity of soil at the experiment site

The variants of the experiment	The biological activity of soil		
	Cellulose-digesting activity	Ammonifying activity	Proteasic activity
Fertilizers with a 3-year composting period	34.82	7.82	1.11
Fertilizers with a 5-year composting period	44.05	7.59	1.36
Control sample	27.67	6.67	0.51
LSD_{05}	14.94	0.72	0.45

* – the differences at the 5 % level of significance are not reliable

Table 6. The agrochemical parameters of soil (2017).

The variants of the experiment	The agrochemical indicators				
	Mg per 100 g of soil (the degree of availability)			pH (acidity level)	Humus, % (availability)
	P_2O_5	K_2O	NO_3		
Fertilizers with a 3-year composting period	3.46 (low)	1.88 (very low)	0.27 (very low)	5.68 (close to neutral)	0.43 (very low)
Fertilizers with a 5-year composting period	1.86 (very low)	0.73 (very low)	0.26 (very low)	5.47 (slightly acidic)	0.51 (very low)
Control sample	0.97 (very low)	1.36 (very low)	0.03 (very low)	5.27 (slightly acidic)	0.11 (very low)

Table 7. The content of heavy metals in the ameliorated soil of the sand quarry.

The variants of the experiment	The content of metals in soil, mg/kg				
	Cu	Cd	Zn	Pb	Ni
Fertilizers with a 3-year composting period	3.04±0.504	0±0.00	7.21±0.985	1.51±0.376	1.95±0.113
Fertilizers with a 5-year composting period	1.64±0.197	0±0.00	4.17±0.502	1.06±0.261	1.89±0.102
Maximum permissible concentration	3.0	0.5	23.0	32.0	4.0

Table 8. The dynamics in the biological activity of soil at the recultivated site

Variant of the experiment	The parameters of the biological activity of soil			
	2012	2014	2015	2017
Cellulose-digesting activity, %				
3-year composting period	12.50	60.4	76.16	59.30
5-year composting period	10.80	54.3	79.68	49.05
Control sample	19.50	28.0	29.61	25.18
LSD (0.5)	4.94	10.66	18.69	12.25
Ammonifying activity, pH of air environment				
3-year composting period	5.0	9.0	8.30	8.75
5-year composting period	5.67	8.7	8.50	8.75
Control sample	5.25	7.3	7.50	5.75
LSD (0.5)	0.50	0.81	1.05	1.29

The introduction of compost based on sewage sludge in podzol sandy soil contributed to the increased population of ecological and trophic groups of microorganisms, taking part in mineralization of organic matter. For example, the total population of microorganisms determined by direct microscopic examination accounts for $2{,}1\times10^7$ CFU/g. of absolute dry soil. The introduction of compost based on sewage sludge leads to an increase in the population of microbes by 1.5–2.5 times in comparison with control samples. The most active process of ammonification, which is the initial stage of organic matter transformation, takes place after the introduction of compost based on sewage sludge with a 3-year composting period (table 9).

The population of microfungi and actinomycetes in ameliorated soil is not big but positively grows in comparison with control samples. The increase in the population of microfungi in sandy soil under the influence of compost based on sewage sludge also indicates the high level of organic compounds mineralization. The increase in the population of actinomycetes in soil, modified by non-traditional organic fertilizers, indicates quite deep mineralization of hard-to-degrade of nitrogen compounds.

The most significant changes in the population of microflora in happened during the first year of soil optimization. This is due to the development of microorganisms related to the transformation of organic matter.

For the next years of research, the number of ammonifying microorganisms slightly decreases, but their population stays positively higher than control values. The third year of recultivation is characterized by a significant increase in the number of fungi and cellulose-digesting microorganisms, performing the first stage of organic matter humification, and actinomycetes, taking part in its last stage.

In comparison with other groups of microorganisms, actinomycetes use hard-to-digest components of plant tissue due to a more powerful enzymatic apparatus. And this trend keeps on. It's worth noting the low population of nitrifying bacteria in the ameliorated sandy soil of the quarry. The recultivation of podzol sandy soil by non-traditional fertilizers ambiguously affected nitrogen fixers. It was determined that the frequency of occurrence of azotobacter in soil, ameliorated by compost based on sewage sludge, decreases. In general, the occurrence of azotobacter in soil was low (from 3 to 14 %).

One of the research tasks is to evaluate the influence of non-traditional ameliorants on the growth of Scots pine at the recultivated site.

In the variants with 3 and 5-year composting periods, the average height of Scots pine increased by 37.03 и 37.6 times respectively during the whole time of research. In the control variant, the average height of plants during the same period increased by 13.2 times (table 10).

Thus, the analysis of chemical, agrochemical, biological and toxicological parameters of soil in the sand quarry, ameliorated by non-traditional organic fertilizers based on sewage sludge and sawdust of softwood and hardwood, showed that the introduction of fertilizers optimizes soil and ecological conditions and contributes to the intensification of growth of scots pine plantlets. However, because compost with a 3-year composting period is characterized by phytotoxicity, it is more appropriate to use organic fertilizer with a 5-year composting period to reclaim disturbed soils and create forests on them.

Table 9. The dynamics of the microorganism population in podzol sandy soil.

Groups of microorganisms	The experimental period	The variants of the experiment		
		Control sample	Fertilizers with a 3-year composting period	Fertilizers with a 5-year composting period
Total population, millions of CFU / gram of absolute dry soil	1	20.63±0.30	47.53±0.39	52.17±0.17
Ammonifiers, millions of CFU / gram of absolute dry soil	1	2.50±0.30	7.00±0.58	3.30±0.48
	2	1.36±0.24	3.82±0.60	2.70±0.36
Actinomycetes, millions of CFU / gram of absolute dry soil	1	0.08±0.03	0.15±0.05	0.23±0.05
	2	0.41±0.01	0.70±0.06	0.78±0.07
Micromycetes, thousands of CFU / gram of absolute dry soil	1	0.7±0.03	2.1±0.25	4.2±0.04
	2	7.0±0.41	17.6±0.44	24.1±2.20
Cellulose destructors, %	1	5.3±1.33	4.0±0.05	18.7±2.67
	2	32.0±2.16	41.0±3.16	34.0±2.15
Nitrifiers, thousands of CFU / gram of absolute dry soil	1	0.28±0.01	0.28±0.01	0.27±0.01
	2	0.31±0.01	0.31±0.01	0.30±0.01
Nitrogen fixers, %	1	10.0±1.15	10.0±2.00	3.0±1.00
	2	14.0±1.33	3.0±0.91	6.0±1.33

* 1 – 2010; 2 – 2012

Table 10. The dynamics of growth of scots pine

Variant of the experiment	The height of pine plantlets, cm			
	2010	2014	2015	2017
Fertilizers with a 3-year composting period	7.4	54.8	115.0	274.0
Fertilizers with a 5-year composting period	7.2	66.4	136.30	270.5
Control sample	7.6	55.2	70.0	100.0
LSD_{05}	-*	11.13	31.58	82.11

* – the differences at the 5 % level of significance are not reliable

4 Conclusion

The use of composts based on sewage sludge as a non-traditional ameliorant for recultivation of disturbed soils can help to get rid of many tones of sewage waste, protect the environment, increase soil fertility and contribute to the intensified growth of forest plants.

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