Project Deliverable 5.1:

Guidelines for small and medium WTP for efficient composting

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1. INTRODUCTION

The change in the way of sewage sludge management towards agricultural use, observed in recent years, is a result of the implementation of the Circular Economy strategy in the European Union assuming the transition of the economy from a linear to circular model in which waste becomes a raw material. This strategy assumes a model of economic development in which the following assumptions are met while maintaining the condition of efficiency:

1) the added value of raw materials / resources, materials and products is maximized or

2) the amount of generated waste is minimized and the waste generated is managed in

accordance with the hierarchy of waste management methods, i.e .:

1. Waste prevention
2. Preparing for re-use
3. Recycling
4. Other ways of recovery
5. Neutralization

This means that the processing of sewage sludge using the composting process, which significantly changes the properties of the sludge allows, (i) change the classification of sewage sludge from waste to product, (ii) enables the production of compost which after meeting certain requirements, can be qualified as a soil improver. The processing of sewage sludge for agricultural use is consistent with the Circular Economy strategy, the implementation of which results in:

- reducing the consumption of raw materials (in this case of artificial fertilizers),
- limitation of the amount of landfilled waste,
- an increase in the amount of waste used as part of recovery.

Sewage sludge, generated in the process of wastewater treatment, is municipal waste containing biogenic substances with a high fertilizing potential. The possibility of using sewage sludge is determined by the Council Directive of June 12, 1986 on the protection of the environment, in particular the soil, when sewage sludge is used in agriculture (86/278 / EEC). On the other hand, the rules for the use of sewage sludge as a soil improver are sanctioned by Regulation (EU) 2019/1009 of the

European Parliament and of the Council of 5 June 2019 laying down rules on making EU fertilising products available on the market.

The new regulation replaces the older regulation of the European Parliament (2003) and of the Council EU on fertilizers and covers all types of fertilizers (mineral, organic) and other fertilising products: soil improvers, growing media, growth promoters, etc. The regulation is part of the EU's Circular Economy Action Plan. It harmonises the standards for fertilizers obtained from organic or secondary raw materials in the EU and creates new opportunities for their production and sale on a large scale, where waste is turned into fertilizer material.

Under the regulation, EU fertilising products bearing the *CE* marking will have to meet certain requirements in order to have access to the EU internal market. They concern, inter alia: mandatory maximum levels of pollutants, the use of specific categories of ingredients and labeling.Using the fertilizing potential of sewage sludge is difficult due to the potential threat to the environment. The processing of sewage sludge in the composting process fundamentally changes the properties of the manufactured product and qualifies it for agricultural use. Composting sewage sludge is practically the only biological treatment method resulting in a product that can be used for agricultural purposes.

2. FIELD STUDIES - Composting

The aim of the research started at the beginning of 2018 was to determine the influence of the proportion between the amount of components making up a mixture of organic materials on the course of the sewage sludge composting process. The high content of the total nitrogen in mechanically dewatered sludge generally in the range of 2÷7% dry mass causes a low value of the C/N ratio. As a result, composting sewage sludge requires the use of additional material (supplement) with a high concentration of organic carbon and low nitrogen content during formating of compost mixture. formation. Practically, a component that modified the C/N ratio in the batch and decided to meet the basic criterion conditioning the correct course of composting was a straw. Because straw is hard to access material research in the context of reducing the share of straw in the batch which determines the correct course of composting should be considered as necessary and expected by companies using this technology for municipal sewage sludge management.

The research was carried out in two parts.

Part I.

Four series have been planned during field research. Each series lasted about 5 months and consisting in monitoring the composting process carried out in windrows of approx. 50 m^3 each. In both series a different proportion between components was used. The basic components were: mechanically dewatered sewage sludge, barley straw, wood chips and mature compost (inoculum). In the first stage two series have been done. In the series no 1 the mass ratio between components forming the compost mixture was respectively 4:1:(0.5+0.5), as described later in the report as 4:1:1. In the series no 2, the mass ratio between the components was respectively 8:1:(1+1), as described later in the report as 8:1:2. Each series was repeated in stage no II.

The research was carried out on an industrial scale using the technology of roofed windrow with a length of approx. 70 m and the dimensions of the trapezoidal cross-section: 3 m - width of the lower base and 1.5 m - height, periodically turned. The research was carried out at the sewage treatment plant in Goleniów. The total area of the concrete composting place with roofing is 2.400 m^2. The parameters of the formed windrows (pictures 1÷3) were as follows:

- working plate length 60 m
- width of the working plate 40 m
- the maximum length of the windrow is 54 m
- width of the windrow base 3 m
- initial windrow height 1.6 m
- height of the windrow with the ready preparation 0.9÷1.1 m.

The produced composts were used in field studies involving the cultivation of selected plant varieties and the assessment of various indicators describing the obtained yields and the impact of compost on soil conditions.

Picture 1.

Picture 2.

Picture 3.

During field tests, compost samples for laboratory tests were systematically taken from each windrow. Laboratory tests consisted of qualitative and quantitative analysis of selected parameters forming four groups, including: basic physicochemical indicators, heavy metals, chemical fractions of heavy metals and humic compounds. The type of indicators that were analyzed corresponds to the requirements set out in national regulations regulating the principles of agricultural use of compost produced on the basis of municipal sewage sludge, having the status of organic fertilizer or plant conditioner. The national and EU regulations regarding the rules of direct use of sewage sludge on agricultural land were also taken into account.

The research showed that the composting process of the sludge proceeds correctly even at the initial C/N ratio equal 10. It is much lower than the recommended value, i.e. 15÷25. It turned out that if there is more sludge than straw in the charge then the temperatures inside the compost windrows are higher and the duration of the thermophilic phase is longer (Fig. 1).

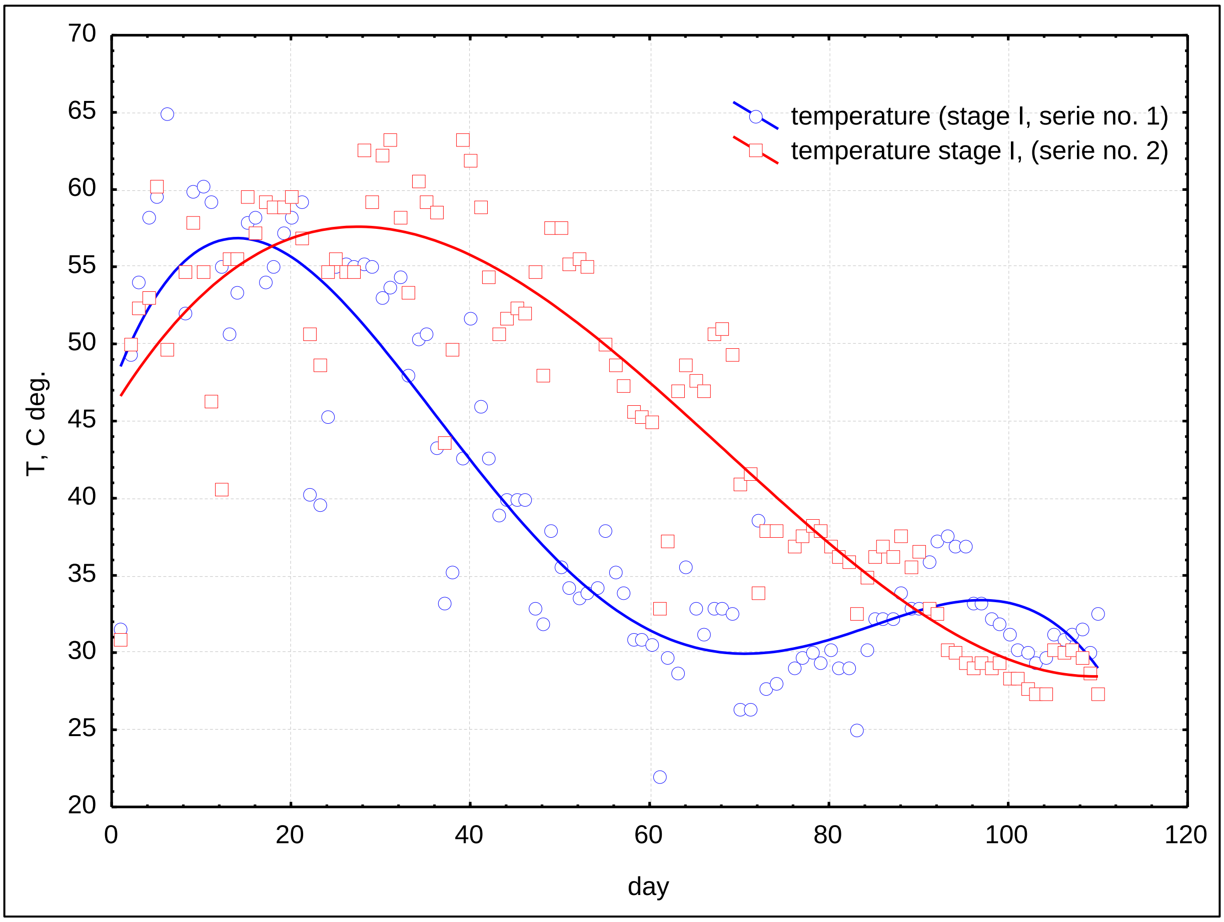

Figure 1.

In all four conducted compost tests, there were changes in the concentration of organic carbon and nitrogen as expected. The process of mineralization of the organic substance caused a constant loss of total organic carbon. At the same time the nitrogen content in the first phase of composting decreased and then gradually increased. The initial drop in nitrogen concentration was related to the release of NH_4^+ ions and the emission of ammonia in the gas form (NH_3) which could increase odor nuisance. The slow increase in nitrogen concentration in the compost during the maturity phase should be considered favorable due to the fertilizer values of this element.

The transformation of organic matter in the composting phase leads to the formation of macromolecular compounds with the character of organic polymers. This process is called humification and the resulting substance with an extremely complex molecular structure is called humium. The precursor of humic compounds are mainly lignin, cellulose and hemicellulose. From these ones various products are formed i.a.

amino acids and phenol. Phenol constituting a basic component of formed humic acids as a result of complex enzymatic reactions. In the initial phase of transformation of organic matter during the humification process, fulvic acids (FA) predominate which over time transform themselves into humic acids (HA). Change in organic carbon forms occurring in the form of so-called nonspecific and specific humic compounds during composting is the basis for determining indices that allow to evaluate the progress of the humification process defined as HA/FA and HA/Corg. The first index is described by the ratio of the carbon of humic acids to carbon of fulvic acids and this is expressed by the abbreviation PI (Polymerisation Index). The second index represents the percentage of carbon of humic acids in relation to the total organic carbon and is referred to as HI (Humification Index).

During the composting, large changes in the content of humic substance were observed. In the first series the 60% decrease of the FA content in relation to the value of this parameter from the beginning of composting was found. In series no.2 this decline was more pronounced and amounted to nearly 50%. At the same time, an increase in the HA content in both series was found. In the case of series no.2 the increase was around 13%. The conversion of fulvic acids into humic acids is one of the determinants of the progress of the humification process. Humic acids could be additionally generated from other humus substances available in the compost. A similar tendency was observed in the series no.2 of second stage where the concentration of KF dropped by 48% and KH increased by 3%. However, in the series no.1 the changes in HA and FA content deviated from the expected .

PI and HI coefficients are commonly used to describe the transformation of humic substance during composting. The values of both humification indices, in the tested windrows during 2nd stage grew but not uniformly. In the series no.1, the PI index increased by nearly 66% and in the second series by 228%. The average initial values of the discussed index were similar for both windrows and amounted to 2.13 and 2.38 respectively. These data indicate that in the initial phase of composting low molecular weight fractions of fulvic acids dominated in both heaps. In the series no.2 of the 2nd stage, the increase in the PI index value amounted to 213%. Assuming that the value of the PI index in the range of 3.6÷6.2 is characterized by mature compost. The moment in which the compost produced during research reached maturity corresponds to about 70 days for the series no.1 and about 40 days for the series no.2 of 1st stage. At the same time, the humification process during the series no.2 was proceeding more stable as evidenced by the dynamics of changes in the PI index value. Therefore, it can be concluded that the duration of the thermophilic phase, which was much longer in the series no.2, has a significant influence on the speed of the humification process. Similar conclusion regarding changes in the PI index during the two series in 2nd stage was not so unambiguous. Generated linear regression lines describing changes in the PI index value in 2nd stage (Fig. 3) compared to 1st stage (Fig. 2), indicate small changes in this parameter over time. At the same time, a large spread of results is visible resulting in a low value of the determination coefficient expressing the quality of the fit of the model to the actual data.

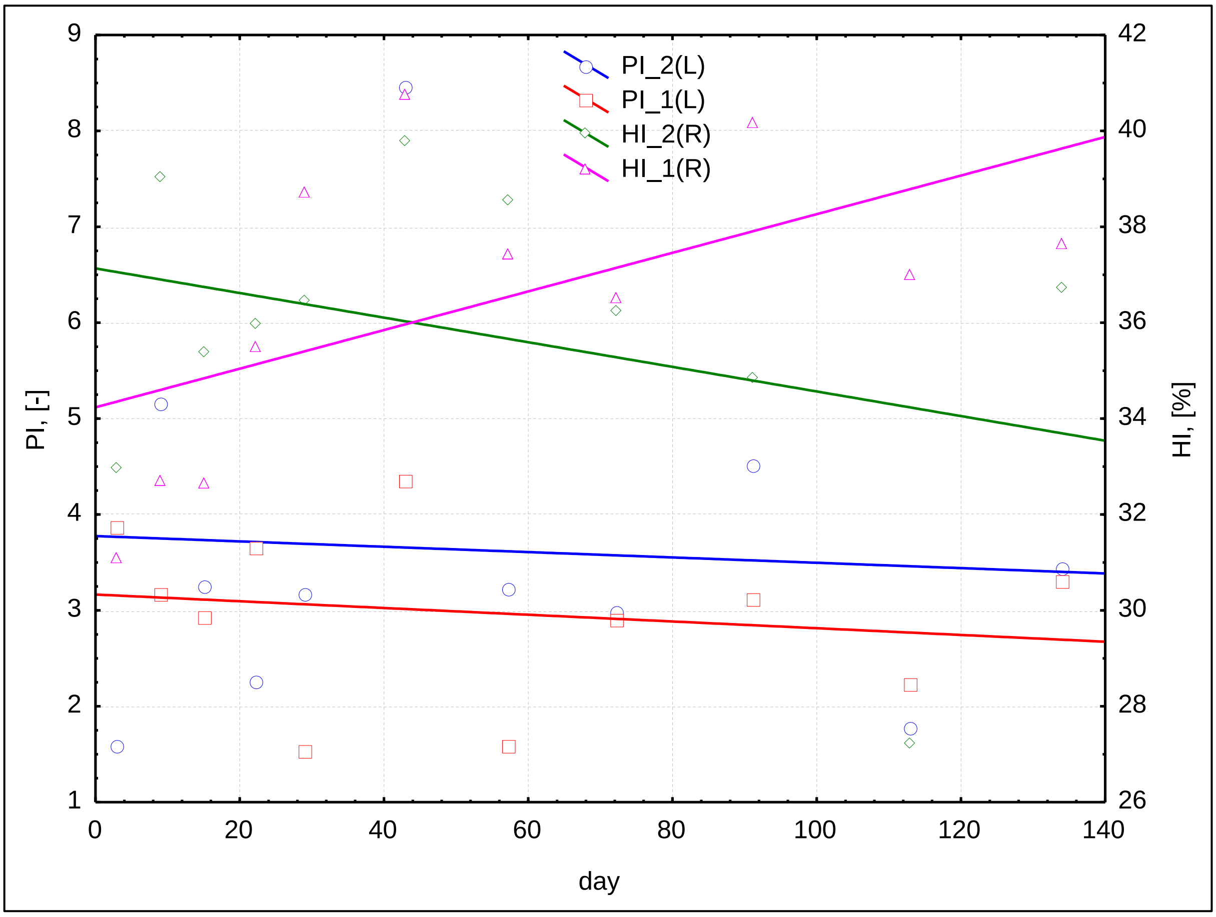

Figure 2.

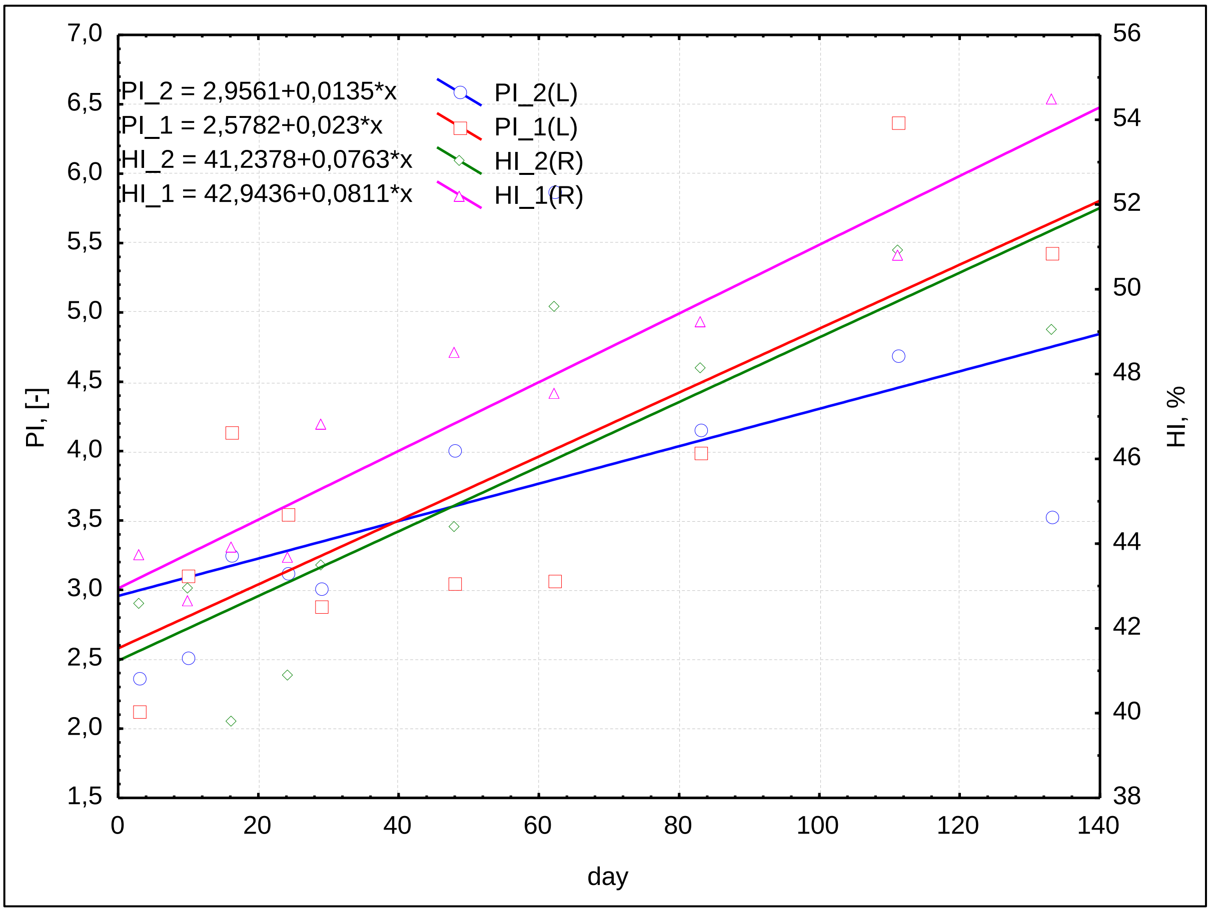

Figure 3.

The content of heavy metals in sewage sludge clearly determines the possibility of their agricultural use. In this regard, the national regulations apply - the Regulation of the Minister of the Environment of February 6, 2015 on municipal sewage sludge (Journal of Laws of 2015, item 257)[1] and the Council Directive of June 12, 1986 on the protection of the environment, in particular soil when sewage sludge is used in agriculture (86/278/EEC) (EU[2]). The use of sewage sludge as a soil improver is sanctioned by Regulation 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on making EU fertilising products available on the market (EU[3]).

When assessing the results of laboratory analyzes concerning the content of heavy metals in sewage sludge and compost samples in both test stages, it should be stated that in no case exceeded the limit values set out in separate regulations[1,2,3].

In general, concentrations of heavy metals during composting in all four series grew. The observed increases were related to the successive loss of organic matter content causing a drop in dry matter. In an environment similar to neutral (pH≈7) heavy metals practically do not form soluble compounds. The total content of heavy metals does not change significantly but in terms of the dry mass the concentration increases.

Speciation analysis allows to mark the chemical forms of a given element in the same sample of compost. The content of heavy metals that have been bounded in the form of various compounds is the result of the natural balance being established depending on environmental conditions. The partial objective of this analysis was to estimate the risk associated with the presence of mobile forms of heavy metals i.e.: nickel, copper and zinc constituting real threats to the environment. It is believed that the binding of heavy metals in the solid phase during the composting process e.g. in the structure of humic compounds and clay minerals, is extremely strong compared to other chemical forms. Thus, the risk of release of heavy metals to the soil medium and their bioaccumulation in crops is reduced.

Separation (fractionation) of heavy metal to different chemical groups characterized by specific properties was carried out in accordance with the Tessier method. According to this method, five groups are identified, i.e.: exchangeable metals (fraction I), metals associated with carbonates (fraction II), metals associated with hydrated iron and manganese oxides (fraction III), metals bound to organic matter (fraction IV) and metals associated with silicates (fraction V). Fractions I and II are treated as unstable. It mean that heavy metals connected with these fractions can be released to the environment. However, in fractions IV and V metals are permanently connected.

Results of the speciation analysis of the compost samples collected in both stages showed that during the composting large changes occur as to the allocation of Ni, Zn and Cu in all fractions. Lines of trend depicting the directions of transformation of chemical forms of the elements determined during composting, in both stages, generally show that the share of metals in the fractions I and II decreases and increases in fractions IV and V. Average nickel content in fraction IV and V in the mature compost obtained in each series accounted for over 97% of the total content. This means that the risk of toxic effects of nickel in the case of agricultural use of compost is practically non-existent. A similar trend was found in the case of copper. Zinc accumulated to a lesser extent in fraction IV and V where the average percentage observed was c.a. 50%.

Part II.

The research was carried out in static composting conditions with forced aeration, running under a cover with a semi-permeable membrane of the GORECover type (pictures 4÷6). In accordance with the composting technology recommended by the manufacturer, one compost test was carried out without the addition of straw, using the mass ratio between sludge and wood chips of 1:1 and additionally one test with addition of barley straw to the mixture of sludge with chips, in a proportion of 2:1:1, respectively.

Picture 4.

Picture 5.

Picture 6.

In part of the field studies, two independent series (no. 1.2 and no.2.2.) were planned. Both series lasted about 9 weeks. The first compost test started on November 24, 2020 and ended on January 26, 2021. The second attempt lasted from December 16, 2020 to February 8, 2021. The raw material for composting was dewatered, partially stabilized sewage sludge from the municipal sewage treatment plant in Goleniów. About 50% of the weight of mechanically dewatered sewage sludge was used as a structure-forming material. Composting was carried out under a cover with a semi-permeable GORECover® membrane, in conditions of intensive aeration by forcing air through channels located in the concrete floor of the reactor. The second compost test was carried out using the same process conditions. The difference was that barley straw was used in addition to the sediments and chips to prepare the charge in a mass proportion between the individual components, respectively 2/1/1. The mass of formed compost windrows in both series amounted to approx. 200 tons each.

The composting process in the second part was tested using a new installation in which no additional carbon source is to be used. According to this technology, the dewatered sludge is mixed with wood chips only, which is supposed to improve the porosity of the mixture and increase the air flow efficiency. The process takes place under the cover of a semi-permeable membrane in conditions of intense air flow forced by the work of radial fans. In these circumstances, the use of straw in series no 2.2 was to test the effect of supplementation on the quality of the compost obtained after 9 weeks of composting. The observed organoleptic properties smell, moisture and consistency of the mixture of sludge with wood chips and straw, which were found during series no.2.2, indicated an unfavorable effect of supplementation. This could be due to the increased water retention associated with the presence of straw. Consequently, the increasing air flow resistance resulted in lower oxygenation and local anaerobic zones. Contrary to series no.1.2, where a 22% loss of om was found, in series no.2.2, the content of this parameter practically did not change after 9 weeks of composting. In bouth series, there were changes in the concentration of organic carbon and nitrogen as expected (Fig. 4).

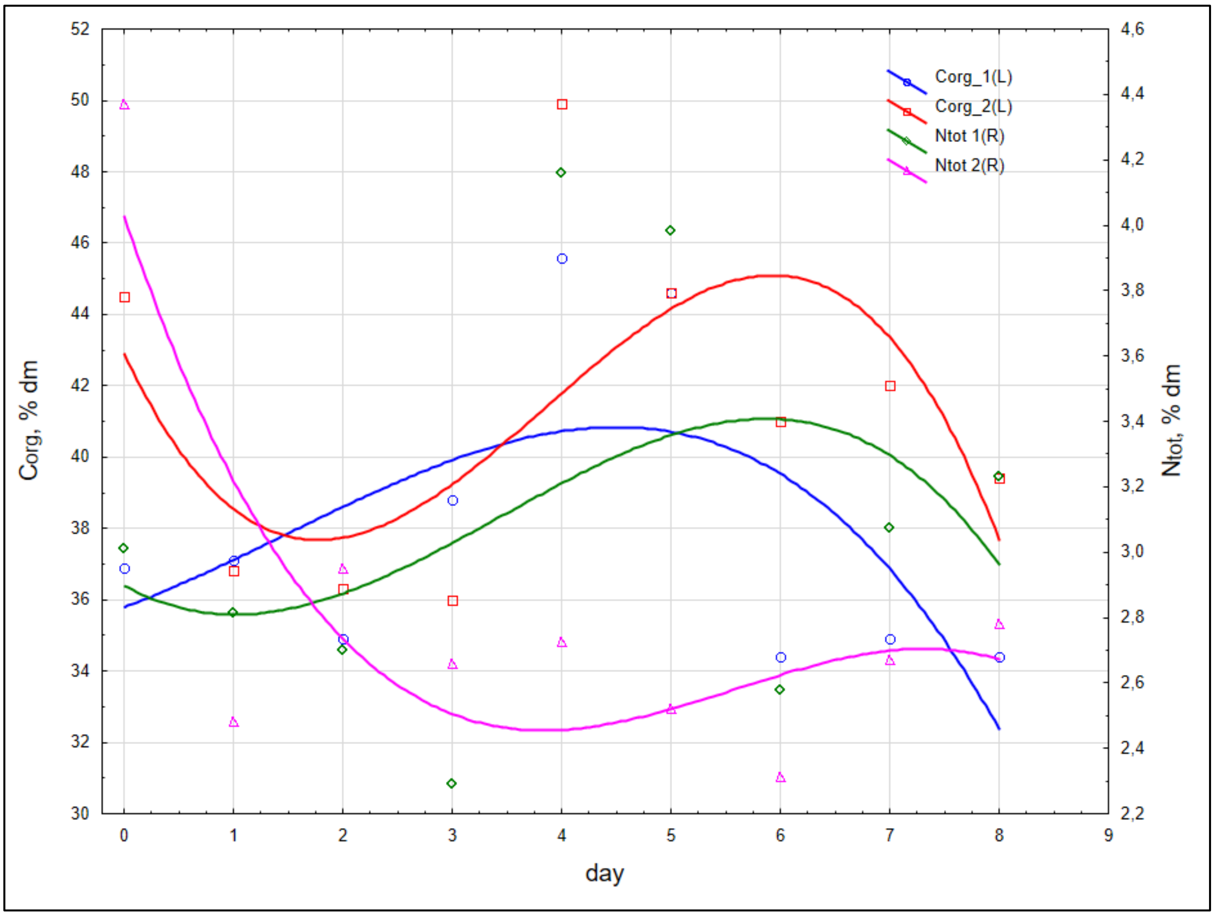

Figure 4.

The process of mineralization of the organic matter caused the loss of total organic carbon, while the nitrogen content in the first phase of composting decreased and then increased. The initial decrease in nitrogen concentration was related to the condensate outflow, saturated with NH_4^+ ions released as a result of ammonification. Conducting periodic measurements of NH_3 content in the post-process air, no presence of this gas was found.

Process conditions mainly slightly acidic in the initial phase of composting are not conducive to shifting the equilibrium in the system: $NH_4^+ \leftrightarrow NH_3$, towards ammonia gas. In series no.2.2, the decrease in the concentration of organic carbon (11%) and total nitrogen (10%) was similar, which consequently did not change the value of the C/N parameter. However, in series no.1.2 the increase in this parameter was approximately 33%.

The research results showed that the contents of the tested heavy metals in mature compost used as a soil improver are below the permissible values, except for nickel. In series no.1.2, the concentration of Ni exceeded the limit value by 53%. As in the used sewage sludge the average nickel concentration in both series was 13.25 mg/kg dm, the increase in Ni content in the compost was the result of secondary contamination which could have been the result of the chipping method used or the contamination of the biomass used. In this situation, the research on the content of chemical forms of heavy metals occurrence becomes practical. In the case of nickel, over 98% is bound in fractions IV and V treated as immobile. Nickel present in these fractions is permanently bound in the solid phase of the multiphase medium-compost, which guarantees it is not bioavailable. Generally, it was observed that during composting, the shares of the remaining elements Zn and Cu, related to fractions IV and V, systematically increased.

Laboratory tests, as in part no I, included determination of the content of humic acids resulting from the humification process of organic matter. To evaluate the course of humification, PI and HI indices were used, calculated on the basis of the carbon content in aqueous solutions obtained as a result of extraction of the determined forms of humic acids. It was found that the PI index is the appropriate indicator to describe the effectiveness of humification the value of which increased in the case of series no.1.2 from 0.7 to 1.0 (Fig.5)

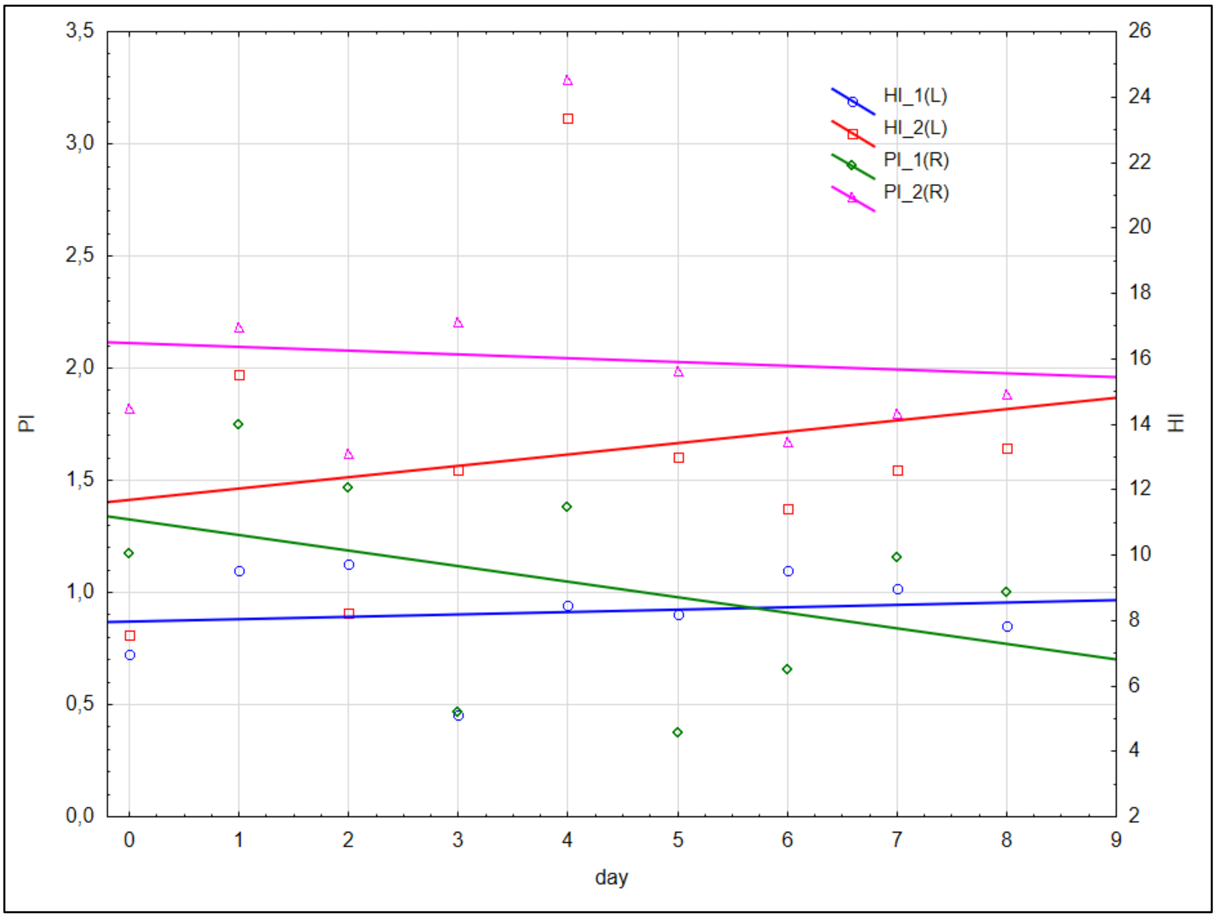

Figure 5.

Relatively low values of this index suggest a short time of the composting process. The currently used technology eliminates or limits the compost maturation phase which as a rule takes place in the conditions of periodically turned windrows. As a consequence, the produced compost can reach the level qualifying it as a biologically stable material, but not mature. It should be emphasized that the temperature inside the piles monitored during both series, even after 9 weeks of composting, indicates a high value. Thus, the assessment of the degree of biological stability of the produced compost should be confirmed by performing a self-heating test carried out with the use of a Dewar's vessel.

3. FIELD STUDIES - Agricultural use of compost

The composts produced in part I were used in field studies involving the cultivation of selected plant varieties and the assessment of various indicators describing the yields obtained and the impact of compost on soil conditions. As part of these activities, control field tests were carried out, involving the use of compost as an organic fertilizer in agricultural crops (sowing spring wheat or spring barley). In each year of the experiment, collective soil samples were collected from each plot from a depth of 0-25 cm for laboratory analyzes. Samples for the determination of the content of mineral nitrogen were taken from layers 0-30 and 30-60 before the application of composts and 3 weeks after application from a depth of 0-90 after the plants were harvested. The main objective of the study was to evaluate the effects of agricultural use of various composts produced in the GWIK wastewater treatment plant in Goleniów. The specific objectives were as follows:

- evaluation of the effects of using composts produced in a sewage treatment plant based on sewage sludge and straw on the properties and functions of soil,
- evaluation of the effects of using composts produced from sewage sludge and straw on plant yield and quality,
- evaluation of the possibility of agricultural use of compost,
- risk assessment of agricultural use of composts produced from sewage sludge and straw,
- comparison of composts effects obtained from different composting technologies,
- developing recommendations for the agricultural use of compost produced from sewage sludge and straw.

In the experiment 8 composts characterized by different C/N ratio and maturation time were tested. All types of the compost were produced from the same sludge (municipal sewage treatment plant in Goleniów) and cereal straw.

Schedule and technological details of the analyzed compost types:

Compost no. 1

produced- autumn 2018,

carbon to nitrogen (C/N) ratio = 20,

the time of establishing the compost prism: spring 2018

maturing time: 4 months in the spring-summer season

Compost no. 2

produced - autumn 2018,

carbon to nitrogen (C/N) ratio = 15,

the time of establishing the compost prism: spring 2018

maturing time: 4 months in the spring-summer season

Compost no. 3

produced - spring 2019

carbon to nitrogen (C/N) ratio = 20,

the time of establishing the compost prism: spring 2018

maturing time: 8 months in the spring-summer-autumn-winter season

Compost no. 4

produced - spring 2019

carbon to nitrogen (C/N) ratio = 15,

the time of establishing the compost prism: spring 2018

maturing time: 8 months in the spring-summer-autumn-winter season

Compost no. 5

produced - spring 2019

carbon to nitrogen (C/N) ratio = 20,

the time of establishing the compost prism: autumn 2018

maturing time: 4 months in the autumn-winter season

Compost no. 6

produced - spring 2019

carbon to nitrogen (C/N) ratio = 15,

the time of establishing the compost prism: autumn 2018

maturing time: 4 months in the autumn-winter season

Compost no. 7

produced - autumn 2019

carbon to nitrogen (C/N) ratio =20,

the time of establishing the compost prism: autumn 2018

maturing time: 8 months in the autumn-winter-spring-summer season

Compost no. 8

produced - autumn 2019

carbon to nitrogen (C/N) ratio = 15,

the time of establishing the compost prism: autumn 2018

maturing time: 8 months in the autumn-winter-spring-summer season

3.1. Methodology

The field studies were conducted from autumn 2018 to autumn 2020 in the fields of the Agricultural Experimental Station in Baborówko (RZD Baborówko), belonging to the Institute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB). The RZD Baborówko, located in the Wielkopolskie Voivodship, is specialised in crop production especially winter wheat, spring barley, winter rape and maize. It has the equipment for measuring the plant growth, a plotter harvester, a field harvester with a yield meter, and an experienced team of employees.

The total field experiment area was 0.07 ha, covering 30 fields of 21 m^2 (6 x 3.5 m). The plots formed a compact block with uniform soil cover. The experiment was carried out on soil with texture of sand and loamy sand , slightly acidic reaction (pH 5.7 - 6.3 in 1M KCl) and low organic carbon content (0.6 - 0.7%). During the experiment the precipitation was quite low, in all years significantly below the long-term average. The same treatments were applied on all plots. Compost and straw were mixed with the soil by means of a soil ripper connected to the tractor. The control treatments were the plots with straw left for ploughing (control 1) and straw left for ploughing with RSM (control 2). All experimental treatments had 3 repetitions (Table 1) and the location of particular variants was chosen at random.

Table 1. Scheme of plot experiments in the AES IUNG-PIB in Baborkówko

C_2018_III 25	**K4_W_2019_I I 26**	**K7_J_2019_II 27**	**K6_W_2019_ I 28**	**C_2018_I 29**	**K8_J_2019_I 30**
K1_2018_II 19	**K8_J_2019_III 20**	**K3_W_2019_II 21**	**K2_2018_III 22**	**K5_W_2019_I 23**	**K6_W_2019_II 24**
C_RSM_2018_ I	**K2_2018_I**	**C_RSM_2018_II I**	**K1_2018_III**	**K3_W_2019_II I**	**K1_2018_I**

13	14	15	16	17	18
K6_W_2019_III 7	K5_W_2019_II 8	K4_W_2019_III 9	K8_J_2019_II 10	K2_2018_II 11	C_RSM_2018_II 12
K7_J_2019_I 1	K3_W_2019_I 2	K5_W_2019_III 3	C_2018_II 4	K7_J_2019_III 5	K4_W_2019_I 6

Explanation of the symbols and abbreviations used in the table (Roman numerals indicate the successive replications of the variant concerned):

K1_2018 – compost 1 – application autumn 2018

K2_2018 – compost 2 – application autumn 2018

K3_W_2019 – compost 3 – application spring 2019

K4_W_2019 – compost 4 – application spring 2019

K5_W_2019 – compost 5 - application spring 2019

K6_W_2019 – compost 6 - application spring 2019

K7_J_2019 – compost 7 - application autumn 2019

K8_J_2019 – compost 8 - application autumn 2019

C_2018 – control straw (since 2018)

C_RSM_2018 - control straw + RSM (since 2018)

Simplified timetable of field works

Year 2018

Autumn 2018 - delineation of experimental plots with the size of 21 m^2. Soil sampling for determination of the initial physico-chemical properties. Leaving straw on control treatments and cleaning straw from treatments dedicated to compost application. Application of composts No. 1 and 2, produced in early October 2018. Soil sampling 3 weeks after application of the composts.

Year 2019

Spring 2019 - application of composts No. 3, 4, 5 and 6. Soil sampling 3 weeks after application of composts and sowing of spring barley on all plots.

Autumn 2019 plant harvest; after plant harvest, application of composts No. 7 and 8. Soil sampling 3 weeks after application of composts. Leaving straw to be mixed with soil on control treatments and other plots.

Year 2020

Spring 2020 - sowing of spring wheat on all plots.

Autumn 2020 plant harvest. Soil sampling for final condition assessment.

Picture 7. Application of compost on experimental plots.

Chemical composition of plants reflected the data obtained for soils, indicating the consistency of the obtained results. There were no statistically significant differences in the content of trace elements in straw and grain. The current legislation (Commission Regulation (EC) No 1881/2006 of 19 December 2006) only sets limits for cadmium (0.1 $mg \cdot kg^{-1}$) and lead (0.2 $mg \cdot kg^{-1}$) in cereal grains. Their contents in barley grains in the post-field experiment were several times lower than the permitted contents. Therefore, the fertilization of the soils with the composts under study allows for the production of uncontaminated high quality grain, not deviating in this respect from the grain produced by mineral fertilization. The study did not show any risk to the environment and the quality of food and feed from the use of the applied composts based on sewage sludge and straw.

It can be assumed that the output of metals with high yields fully balances the small amounts of metals introduced into the soil with the composts.

3.2. The impact of composts on yield and quality of crops

The primary purpose of soil fertilization is to achieve an adequate plant yield. The most reliable for the assessment of the impact of composts on barley yields are the yield measurements of 2020, as they reflect the impact of composts at a similar level of soil transformation (at least one year after application). The effect of composts on plant yield may be direct, resulting from the activation of compost fertilizer components, but also indirect - by modifying water retention in soil or activity of microorganisms in the root zone.

Composts K3-K8 significantly increased the yield of straw and spring barley grain in 2020 compared to objects with tilled straw (Fig. 6 and 7). Composts K1 and K2 did not provide such an effect. Due to the fact that the individual objects did not differ significantly in terms of pH and abundance of available fertilizer components, the positive effect of the compost is most likely to be associated with their positive effect on soil water retention and soil biological processes, supporting the development and resistance of plants to stress conditions. Both 2019 and 2020 were characterized by low level of precipitation, compared to the multi-annual average.

Among the composts, the highest yields were obtained for composts K7 and K8 with a long ripening period and applied in autumn 2019. This effect, in turn, can be attributed to the nature of the individual fractions of organic matter derived from the compost and the shorter time after the application of the compost into the soil.

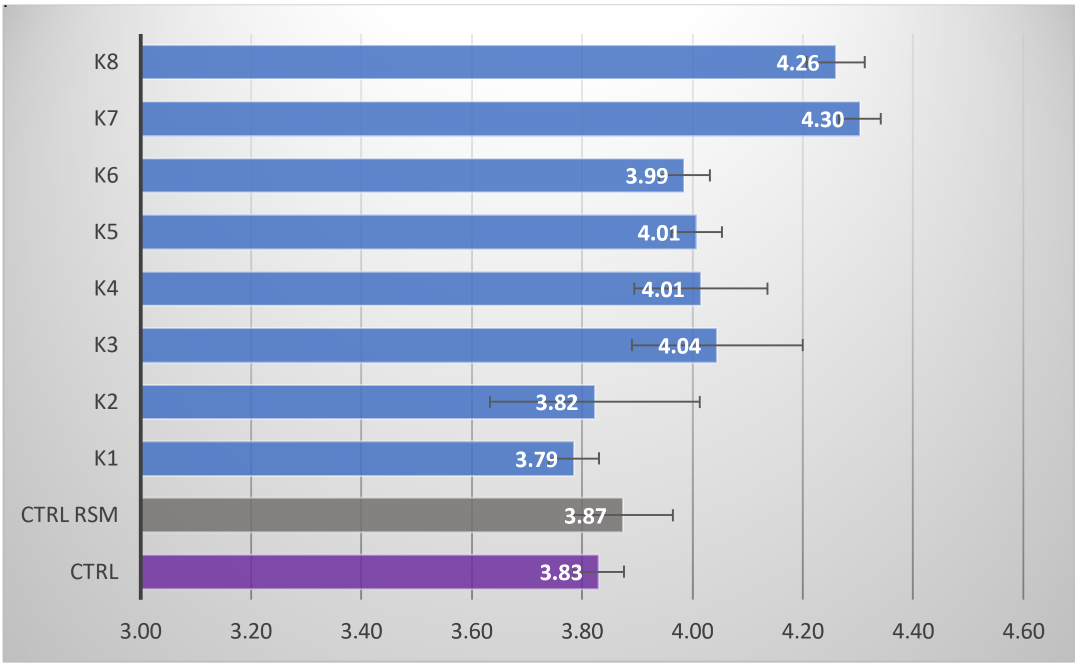

Figure 6. Spring barley straw yield (t·ha^{-1}) in autumn 2020. (the whiskers in the graph indicate the

standard deviation from the replication of the variant)

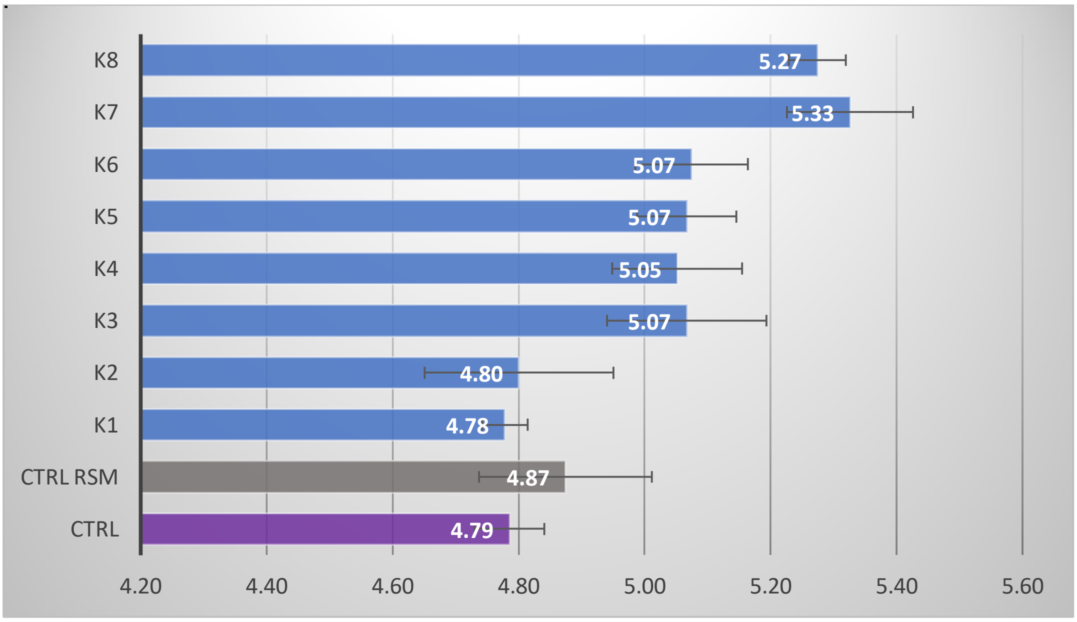

Figure 7. Spring barley grain yield (t·ha^{-1}) in autumn 2020. (the whiskers in the graph indicate the standard deviation from the replication of the variant)

The quality of the crop is evidenced by the content of individual elements (macro and microelements) which determine the balance of nutrients in food or feed. Their content may also explain the differences in yield, in case of deficiency of individual elements. The straw and grains did not show statistically significant differences in the content of nitrogen, potassium, magnesium and micronutrient e.g. manganese (Tab. 2). Therefore, the use of compost does not cause deficiencies of essential elements compared to mineral fertilization.

Table 2. Macro and micronutrient content of spring barley straw and grains in autumn 2020.

Combination	Straw				Grain			
	N	Mn	Mg	K	N	Mn	Mg	K
	%	mg/kg			%	mg/kg		
CTRL	0,87	17,0	1241	20518	1,72	16,5	1661	7091
CTRL RSM	0,68	14,3	1072	18824	1,72	19,3	1652	7619
K1	0,70	18,1	1145	17982	1,72	20,6	1771	8044
K2	0,82	18,7	1153	18527	1,74	18,4	1664	7377
K3	0,85	17,4	1237	18451	1,64	17,9	1679	7522
K4	0,83	20,0	1183	18615	1,74	17,6	1590	6913
K5	0,70	17,5	1256	24245	1,61	18,5	1674	7680
K6	0,79	22,3	1223	19176	1,87	18,7	1679	6977
K7	0,64	15,9	995	19153	1,74	15,2	1511	6705
K8	0,71	18,3	1185	18930	1,71	16,9	1701	7521

Picture 8. Comparison of plant growth in 2020 with insufficient rainfall - left: control with straw ploughing, right: compost K7.

4. RECOMMENDATIONS

4.1. Composting process

Based on the conducted studies on composting sewage sludge aimed at assessing the impact of reduced or completely eliminated supplementation in conditions of periodically turned windrows without aeration - Part I, as well as windrows with forced aeration isolated from the atmosphere with a synthetic membrane - Part II, the following conclusions can be formulated:

Part I

1. The mass ratio between raw materials, forming a batch for the composting process, in the form of: dewatered sewage sludge and barley straw, constituting the basic (balanced) source of organic carbon and nitrogen, structural material and inoculum in the form of wood chips and mature compost, amounting to 8/1/1/1 guaranteeing the value of the C/N≈10, enables the right course of the composting process.
2. There was no inhibitory effect of increased concentration of total nitrogen in the compost associated with high concentrations of this element in sewage sludge (7.48% and 7.54% d.m. in both stages) on the course of the composting process through the interaction of toxic nitrogen species e.g. in the form of ammonia, which is formed as a result of decay of protein substances which indicates the proper oxygenation of the prism thus preventing the formation of anaerobic conditions.
3. The content of heavy metals in sewage sludge did not exceed the limit values allowing for their agricultural use and thus it is possible to use sludge for processing in the biological process under aerobic conditions for the production of certified compost as organic fertilizer in accordance with the requirements of the Act on fertilizers and fertilization.
4. The results of the speciation analysis related to the determination of heavy metal concentrations i.e.: Zn, Cu and Ni in sequentially separated chemical forms isolated from compost samples, characterized by different levels of bioavailability, showed that composting time has a favorable influence to the

allocation of heavy metals by systematic increasing the share of heavy metals bound in stable fractions at the expense of fractions which reliably release elements attached to them.

5. The humification process evaluated on the basis of changes in fulvic acid concentrations transformed into more complex chemical structures including humic acids considered the final effect of these transformations, had a significant impact on the formation of mature compost with a high concentration of humic compounds giving characteristic organoleptic properties i.e. color, aroma and crumbly structure.
6. A reliable indicator describing the effectiveness of the humification process occurring during composting of sewage sludge is the PI index whose value above 3.6 can be considered proper for mature compost provided that the temperature inside the compost windrow within a few days after the last transfer does not rise above the ambient temperature.

Part II

1. In the case of the sewage sludge composting technology with the use of a Gore-Tex membrane cover, it is not recommended to supplement the mixture with mechanically dewatered sewage sludge and wood chips.
2. The high nitrogen content in sewage sludge and a relatively low value of the C / N ratio in the mixture of sludge and wood chips, which is the input for the composting process using intensive aeration and isolation of the windrow with a Gore-Tex membrane, does not pose a threat of gas ammonia emission to the atmosphere
3. The results of the speciation analysis related to the determination of the concentrations of Zn, Cu and Ni in the sequentially separated chemical forms extracted from compost samples, characterized by different levels of bioavailability, showed that with the composting time favorable changes in the allocation of the determined heavy metals consisting in a systematic increase in their share in non-available fractions occurred.
4. During the 12-week composting period, the PI index value did not reach the level of 3.6 considered appropriate for mature compost which suggests the

need for further composting in conditions of periodically turned windrows over a period of at least 2 months.

4.2. Agricultural use of compost

In conclusion, the research has provided the following observations:

1. Almost all compost variants promoted an increase in soil phosphorus availability compared to straw ploughing facilities, and this effect lasted long after the compost was applied
2. In the case of available potassium and magnesium, there was a rapid increase in their availability to plants after application, but in the long term, no differences were observed between fertilization variants.
3. The application of RSM before ploughing the straw resulted in a significant decrease in soil pH, similar to composts 1 and 2. Despite dynamic changes in pH shortly after application of some composts, the pH stabilized in the long term and remained in the neutral range, the most favourable for plants.
4. The nitrate nitrogen content was much higher than in the ammonium form, which is typical for processes occurring in soil.
5. Shortly after compost application only in case of one compost, the amount of nitrates in the soil profile was higher than that of recorded for RSM added to ploughed straw. Also in the long term, the amount of nitrates in the soil was lower after application of compost than after ploughing straw or straw with RSM. Most of the nitrates were located in the topsoil layer.
6. The application of the compost did not cause an excessive concentration of ammonium nitrogen, which can be toxic to plants in excessive amounts.
7. After 1 – 2 years from the application of the compost, the organic carbon content remained at the same level, and no differences were observed between the individual plants.
8. In the majority of compost variants, the activity of microorganisms was higher than in the control variant with straw ploughing.

9. K3-K8 composts used in 2019 stimulated bacterial counts more than composts introduced into the soil in 2018, which may indicate the influence of the time factor since the application of the compost.
10. Some composts stimulated the growth of phosphate dissolving bacteria.
11. The K3-K8 composts significantly increased the yield of straw and spring barley grain in 2020 compared to facilities with ploughed straw. Among the composts, the highest yields were obtained for K7 and K8 composts with long ripening period applied in autumn 2019.
12. The use of composts did not cause shortages of essential elements in comparison with mineral fertilization.
13. No changes were found in the content of potentially toxic elements (cadmium, lead, chromium, mercury) in the soil after the composts application, regardless of the technological variant. These contents were at a level significantly lower than the acceptable limits in the national regulations.
14. Cadmium and lead contents in barley grains in the post-treatment experiment were several times lower than the permissible limits.
15. The comparison of the effects of individual composts provided ambiguous information. Composts K1 and K2 stimulated the increase in the assimilability of phosphorus, potassium and magnesium, especially observed in the short term after their application. The same composts acidified the soil, but this effect was short and subsided in the long term. Composts K7 and K8 caused the lowest content of mineral nitrogen 3 weeks after application, and in the long run these effects were less visible. The effect of stimulating the activity and the number of soil microorganisms does not allow the selection of individual variants of the compost - this effect was different for diversified biological parameters. The highest barley yields in 2020 were provided by composts K7 and K8. Also composts K3, K4, K5, K6 caused an increase in yield in comparison with objects with ploughed straw. In terms of grain quality, there were no differences in the effects of individual composts.

5. CONCLUSIONS

1. The use of the composts tested, produced in the process of windrow composting sewage sludge and cereal straw, does not enrich the soil with undesirable elements. This is due to their low content in the feedstock used to produce the composts as well as application of balanced doses of compost.
2. Fertilization of the soils with the composts tested allows the production of uncontaminated grains, which do not differ in quality from grains produced by mineral fertilization.
3. The tests have not demonstrated any risk for the environment and the quality of food and feed associated with trace elements such as cadmium, lead or mercury.
4. High doses of compost may cause a temporary decrease in soil pH, a phenomenon often observed after application of organic fertilization, associated with mineralization of organic matter.
5. Composts generally increase soil biological activity.
6. When applying the recommended doses, the use of compost does not pose a greater risk of excessive leaching of nitrates to water than the use of mineral fertilisation and straw ploughing.
7. The use of composts increases the yielding of straw and barley grain, especially in dry years, which should be associated most closely with their positive effects on soil water retention and soil biological life, supporting the development and resistance of plants to stress conditions.
8. The use of compost ensures that the soil carbon level is kept constant despite the removal of all straw from the plots.
9. The data obtained do not indicate unequivocally which of the tested compost production technologies gives the best results in terms of fertiliser product quality. Composts K1 and K2 with a short ripening period increased the assimilability of fertiliser components for plants to the greatest extent, but they also caused a decrease in soil pH. On the other hand, composts with a long 8-month ripening period, ripened in spring and summer (K7 and K8) caused the highest increase in straw and grain yield, regardless of the initial carbon/nitrogen ratio. Such a technological process would therefore be most recommended.

6. FINAL RECOMMENDATIONS

Tested composts may be used in agricultural production, including the production of plants for food, without risk. They should be used to the greatest extent for cereal crops as an alternative source of organic matter in the absence of manure. For cereal crops, a rate of 10-15 tonnes of compost per hectare every 2 years is recommended (higher doses on heavier soils), as the most beneficial effect of compost application is observed in the 2nd year after application. It is most recommended to apply the compost in autumn. It should not be used on frozen, snow-covered or flooded soil or during rainfall.

Since high doses of organic matter can cause soil acidification processes, especially on sandy soils with poor buffering properties, the soil should be limed every 3-4 years in order to prevent the pH drop in the soil, in the doses resulting from the analytically determined liming needs.