Investigation of sewage sludge for the purpose of their secondary use as agricultural fertilizer

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Abstract. Substantiated the possibility of using an optimized technology for processing sewage sludge in the production of agricultural fertilizers. The researches have been experimentally tested on a pyrolysis plant - a physical model assembled under laboratory conditions. Selected, calculated and experimentally confirmed the optimal composition of agricultural fertilizer based on sewage sludge. The suggestions allow to increase the production of mineral fertilizers and reduce the accumulation of sewage sludge in the sludge fields of treatment facilities of industrial enterprises.

1. Introduction
Wastewater disposal is carried out on sludge fields, which alienate huge territories. In the world, approximately 83 million tons of sewage sludge (WWS) is generated per year, taking into account humidity, the total mass of world precipitation is approximately 4.15 billion tons, of which 100 million tons are formed in Russia. In the context of increasing requirements for the rational use of natural resources, there is a need for their effective use or recycling. The main methods of recycling and disposal of sludge wastewater in Russia are burial (placement) directly at sludge sites; direct combustion method; anaerobic digestion; composting; lime stabilization [1].

The main disadvantages of almost all of these methods are the use of expensive reagents, high energy consumption and the formation of harmful gases during the processing process.

2. Description of the physical model of the pyrolysis process of sewage sludge in laboratory conditions
The experiment is carried out at temperatures of 800 °C and 400 °C. The physical model of the process of pyrolysis of sewage sludge, developed in the laboratory conditions of Togliatti State University, includes (figure 1): the loading device (1) is performed by a quartz tube, the rector (2) is represented by a tubular muffle furnace (t = 800 °C and 400 °C) and device for receiving finished target products (3, 4). In a tubular muffle furnace (2) was placed a quartz tube (1) with a pre-placed sewage sludge (pre-weighed). An inert gas, in our case argon of the highest quality to remove oxygen, was brought to the quartz tube with the sewage sludge and brought to the temperature that is reached in the pyrolysis unit, or rather 800 °C; 400 °C. And they burned out sewage sludge at the indicated temperatures. Thus, we have achieved the conditions close to the pyrolysis conditions for three hours.
The purge unit of the system consists of a cylinder with an inert gas (1), namely with argon of the highest category. The reactor is a tubular muffle furnace (5), which provides heating to a temperature of 800 °C and 400 °C, in which there is a quartz tube 4 with sewage sludge, a hermetically sealed rubber stopper 3 and a receiving flask 7. A tubular muffle furnace provides heating to a temperature of 800 °C and 400 °C, the synthesis is heated - the gas is kept, thereby heating the waste: wastewater sludge, distillate (moisture) and organic matter go into the receiving flask. At the end of the test, we turn off the installation and wait until it cools completely, then we extract the ash (one of the pyrolysis products) after the pyrolysis installation. Figure 2 shows a physical model of the pyrolysis process under laboratory conditions.

Figure 1. Schematic of the physical model of the pyrolysis plant in laboratory conditions:
1 – gas cylinder (argon of the highest category); 2 – silicone hose; 3 – rubber stopper for tightness;
4 – quartz tube; 5 – tube muffle furnace; 6 – gas and liquid outlet; 7 – receiving flask; 8 – valve.

Figure 2. Physical model of the pyrolysis process in laboratory conditions.

The composition of the gaseous products of pyrolysis of sewage sludge includes hydrocarbons of different classes C_1 – C_{10} (table 1). When simulating a pyrolysis plant at a temperature of 400 °C, measurements were made of the emission of a gaseous pyrolysis product for the 1st; 10th; 60th, 120th and 180th minutes. The gas measurement results are shown in table 1.

It was found that pyrolysis is accompanied by the formation of a liquid hydrocarbon mass (its appearance is an oily, dark brown, homogeneous liquid with a characteristic odor of hydrocarbons, the release of liquid, including water, depends little on the pyrolysis regime). Also, hydrocarbons C_1 - C_{10} (with a specific smell) are released, but the main component for this work is coke (pyrolysis product). Thus, the utilization of sewage sludge by pyrolysis makes it possible to obtain products of different aggregate states.
Table 1. Composition of gaseous products of pyrolysis of sewage sludge hydrocarbons of different classes $C_1$ – $C_{10}$ at a temperature of 400 °C.

| Measurement, time, min. | Concentration of hydrocarbon content. $C_1$ – $C_{10}$ mg / m$^3$ |
|-------------------------|---------------------------------------------------------------|
| 1                       | 2.8                                                           |
| 10                      | 86.35                                                          |
| 60                      | 2844.8                                                        |
| 120                     | 661.2                                                          |
| 180                     | 1342.5                                                         |

2.1. Laboratory study of sewage sludge from sewage treatment plants

After the sewage sludge was burned out, chemical analyzes were carried out for agrochemical indicators of sewage sludge, which must comply with GOST R 17.4.3.07 – 2001 (Nature Protection. Soils) and SanPiN 2.1.7.573 – 96 (Sanitary norms and rules. Soil, cleaning, household and industrial waste, soil sanitary protection. Hygienic Requirements for the Use of Wastewater and Their Sediments for Irrigation and Fertilization). Table 2 shows the requirements for sewage sludge used as fertilizer.

Requirements for the properties of sewage sludge when used as fertilizer [4, 5].

Table 2. Agrochemical indicators of precipitation.

| Indicator name                        | Norm | Method of determination |
|---------------------------------------|------|------------------------|
| Mass fraction of organic substances, % on dry matter, not less | 20 | GOST 26213 |
| Medium reaction (pHsalt)              | 5.5 – 8.5* | GOST 26483 |
| Mass fraction of total nitrogen (N), % on dry matter, not less | 0.6 | GOST 26715 |
| Mass fraction of total phosphorus ($P_2O_5$), % on dry matter, not less | 1.5 | GOST 26717 |

* Sediments with a pH value of extracts of more than 8.5 can be used on acidic soils as organo-lime fertilizers.

2.2. Experimental studies of sewage sludge

2.2.1. Chemical analysis of a model mixture of a sewage sludge sample. The results of chemical analysis for agrochemical parameters of the model mixture of sewage sludge are shown in tables 3, 15, the results of chemical analysis for compliance with the agrochemical parameters of the model mixture of sewage sludge before and after modeling the pyrolysis plant at temperatures of 400 °C and 800 °C, sewage sludge calcined at 130 °C.

According to the results of chemical analysis for agrochemical parameters of a model mixture of sewage sludge after pyrolysis at 800 °C $pH = 10.17 \pm 0.10$ units. The $pH$ value is an alkaline medium, namely, the presence of such ash can only occur on acidified soils. Sewage sludge after thermal drying at 130 °C has a neutral $pH$ of 6.53 ± 0.10 units $pH$ value. Sewage sludge after pyrolysis at 400 °C $pH = 7.74 \pm 0.10$ units. A neutral environment was established.

Thus, the sewage sludge after the pyrolysis plant at 800 °C acquires an alkaline medium ($pH = 10.17 \pm 0.10$ pH units) and fertilizers based on such sludge can be used only on highly acidic soils. Thus, the sewage sludge after the pyrolysis plant at 800 °C acquires an alkaline medium ($pH = 10.17 \pm 0.10$ pH units) and fertilizers based on such sludge can be used only on highly acidic soils. The waste water sludge after the pyrolysis plant at 400 °C has a neutral environment ($pH = 7.74 \pm 0.10$ pH units), is completely dehydrated and disinfected, therefore, it can be used in the production of agricultural fertilizers.

Sewage sludge after treatment with low-temperature pyrolysis (400 °C) fully corresponds to agrochemical indicators, and, therefore, can be used in the production of agricultural fertilizers.
Table 4. Results of chemical analysis for compliance with agrochemical parameters of the model mixture of sewage sludge before and after the analogue of the pyrolysis plant at $t = 400^\circ$C and 800 $^\circ$C and sewage sludge calcined at $t = 130^\circ$C.

| Index                               | Methodology               | Sludge after pyrolysis 800 $^\circ$C | Sludge after pyrolysis 400 $^\circ$C | Sludge after furnace 130 $^\circ$C | Sludge before pyrolysis (raw) |
|-------------------------------------|---------------------------|-------------------------------------|-------------------------------------|-----------------------------------|-------------------------------|
| Nitrite NO$_2$ nitrite nitrogen     | PND F 16.1:2.2:2.3:3.51–08 | 0.431 ± 0.0431 mg/kg                | 0.549 ± 0.0549 mg/kg                | 0.413 ± 0.0413 mg/kg              | 0.306 ± 0.0306 mg/kg          |
| Ammonia NH$_3$ ammonium nitrogen    | PND F 16.2:2.2:3.3:30–02  | 4.164 ± 0.4164 mg/kg                | 5.160 ± 0.516 mg/kg                | 8.786 ± 0.8786 mg/kg              | 15.29 ± 0.153 mg/kg           |
| Nitrate                            | GOST 26951–86              | 15.5 ± 2.325 mg/kg                  | 1750.96 ± 262.64 mg/kg             | 1750.96 ± 262.64 mg/kg            | 38.9 ± 5.835 mg/kg            |
| N nitrogen (Keldahl)               | GOST 26715–85              | 2.04 ± 0.2 %                        | 1.97 ± 0.2 %                       | 1.52 ± 0.2 %                      | 1.12 ± 0.2 %                  |
| Moisture content                   | GOST 26713–85              | –                                   | –                                   | –                                 | 33.6 ± 2.4 %                  |
| Bulk for organic matter            | GOST 27980–88 (organic carbon) | –                                   | –                                   | –                                 | 35.8 ± 3.2 %                  |
| Hydrogen exponent (pH)             | GOST 26423–85              | 10.17 ± 0.10 units pH               | 7.74 ± 0.10 units pH               | 6.58 ± 0.10 units pH              | 6.53 ± 0.10 units pH          |
| Potassium water soluble forts      | GOST 31869–2012            | 30.97 ± 2.17 mg/kg                  | 30.11 ± 2.40 mg/kg                 | 22.11 ± 2.40 mg/kg                | 16.955 ± 2.374 mg/kg          |
| Sodium water soluble forts         | GOST 31869–2012            | 33.88 ± 1.59 mg/kg                  | 33.73 ± 2.62 mg/kg                 | 24.43 ± 2.62 mg/kg                | 19.155 ± 2.682 mg/kg          |
| Magnesium water soluble forts      | GOST 31869–2012            | 34.40 ± 1.28 mg/kg                  | 33.52 ± 2.61 mg/kg                 | 24.83 ± 2.61 mg/kg                | 18.67 ± 2.614 mg/kg           |
| Strontium                           | GOST 31869–2012            | 0.217 ± 0.0434 mg/kg                | –                                   | –                                 | –                             |
| Calcium water soluble forts        | GOST 31869–2012            | 145.05 ± 5.21 mg/kg                 | 144.92 ± 9.49 mg/kg                | 104.92 ± 9.49 mg/kg               | 80.792 ± 8.073 mg/kg          |
| Mass fraction of total phosphorus   | GOST 26717–85              | 27588.98 ± 2526.37 mg/kg            | 27565.65 ± 2711.95 mg/kg           | 20.419 ± 2711.95 mg/kg            | 15352.76 ± 2609.97 mg/kg      |
| P$_2$O$_5$ acid-soluble forms      | GOST 31957–2012 (p. 5)     | 61.0 ± 7.3 mg/kg                     | 274.5 ± 32.9 mg/kg                 | 671.0 ± 80.5 mg/kg                | 286.7 ± 34.4 mg/kg            |
| Hydrocarbons water soluble form     | GOST 31957–2012 (p. 5)     | 9.0 ± 1.1 mg/kg                      | Less 6.0 mg/kg                     | Less 6.0 mg/kg                    | Less 6.0 mg/kg                |
| Carbonates water-soluble form       | GOST 31957–2012 (p. 5)     | 0.15 ± 0.02 mmol/kg                 | Less 0.1 mmol/kg                   | Less 0.1 mmol/kg                  | Less 0.1 mmol/kg              |
| Total alkalinity water-soluble form | GOST 31957–2012 (p. 5)     | 1.0 ± 0.1 mmol/kg                    | 4.5 ± 0.5 mmol/kg                  | 1.40 ± 0.17 mmol/kg               | 1.0 ± 0.1 mmol/kg            |
Table 5. Results of chemical analysis for the compliance of agrochemical parameters of the model mixture of sewage sludge before and after the analogue of the pyrolysis unit at t = 400 °С and 800 °С and sewage sludge calcined at t = 130 °С.

| Index                              | Sludge after pyrolysis 800 °С | Sludge after pyrolysis 400 °С | Sludge after 130 °С | Furnace Sludge before pyrolysis (crude) | Agrochemical standards |
|------------------------------------|-------------------------------|-------------------------------|---------------------|----------------------------------------|------------------------|
| N (nitrogen) (Keldahl)             | 2.04 ± 0.2 %                  | 1.97 ± 0.2 %                  | 1.52 ± 0.2 %        | 1.21 ± 0.20 %                         | Not less than 0.6%     |
| Moisture content                   | –                             | –                             | –                   | 33.6 ± 2.4 %                          | Not standardized       |
| Bulk for organic matter            | –                             | –                             | 35.8 ± 3.2 %        | 35.8 ± 3.2 %                          | Not standardized       |
| Hydrogen exponent (pH)             | 10.17 ± 0.10 units pH         | 7.74 ± 0.10 units pH          | 6.58 ± 0.10 units pH| 6.53 ± 0.10 units pH                  | 5.5 – 8.5 units pH     |
| Mass fraction of total phosphorus  | 27588.98 ± 2526.37 mg/kg      | 27565.65 ± 2711.95 mg/kg      | 20.419 ± 15352.76 ± | 20.4 ± 0.3 %                          | Not less than 1.5%     |
| P2O5 acid-soluble forms            | 27.6 ± 0.2 %                  | 27.6 ± 0.3%                   | 20.4 ± 0.3 %        | 1.5 ± 0.3 %                           |                        |

2.2.2. Plant Growth Experiment. One of the quickest methods for assessing soil quality is the growth measurement method of plant growth control [2].

An experiment was conducted to assess the effect of soil composition on plant growth. Three types of soils were used for the experiment:

1) Sewage sludge after pyrolysis at a temperature of 800 °C in a ratio of 1 part of sludge to 5 parts of peat;
2) Sewage sludge decontaminated and dehydrated after thermo-drying at a temperature of 130 °C for 1 hour, 1 part of the sludge 5 parts of peat;
3) Sewage sludge after pyrolysis at a temperature of 400 °C in a ratio of 1 part of sludge 5 parts of peat.

The essence of the method lies in growing plant seeds in two controlled environments: control - without fertilization - with fertilizer. The tests are carried out at least two parallel samples and at least two plants.

The objects of research in the experiment were the following plants: “Spring cress”, “Dukat cress” and “Old doctor salad mustard”. As a fertilizer, a mixture was prepared: sewage sludge after pyrolysis at a temperature of 800 °C in a ratio of 1 part of sludge to 5 parts of peat.

The result of the experiment showed that plants without fertilization grow the growth of plants with fertilization, on average, 1.35 times lower, moreover, on February 12, 2020, 80% of plants with fertilizers died on the seventh day after germination. Repeated experiment on plant growth, due to unsuccessful first experiment. The following plants were chosen for the test: “Watercress - salad Zabava”, “Watercress - salad Shirokolistny” and “Mustard salad Old doctor”. A mixture was made as a fertilizer: Sewage sludge, disinfected and dehydrated, after thermo-drying at a temperature of 130 °C for 1 hour. 1 part sediment 5 parts peat.

Experiment on plant growth after thermal drying at 130 °C. As a result of the repeated experiment, it was found that the growth of the experimental plants was 1.25 times more intense than in the control ones. In addition, the diameter of the rosettes of fertilized plants is, on average, 1.33 times larger than in the control.

Conducted a third experiment on plant growth. The following plants were chosen for the test: “Watercress - salad Zabava”, “Watercress - salad Shirokolistny” and «Mustard salad Old doctor». Sewage sludge was added to the peat for planting after pyrolysis at a temperature of 400 °C in a ratio of 1 part of sediment to 5 parts of peat.
The experiment after pyrolysis at a temperature of 400 °C in a ratio of 1 part of sediment to 5 parts of peat had a positive effect on plant growth under equal conditions already on the 4th day after planting. And on the 8th day, it can be seen that the diameter of the rosette is significantly higher in the experiment with sewage sludge, and the height of plants from precipitation is higher.

Thus, according to the results of the analysis and experiment, the conclusion follows: the sewage sludge after combustion in a pyrolysis plant at a temperature of 800 °C is not suitable for the experiment on germination and in terms of pH = 10.17 ± 0.10 units. pH, after thermal drying at 130 °C moisture does not completely leave the wastewater sludge, therefore it is better to use wastewater sludge after burning in a pyrolysis plant at a temperature of 400 °C. As a result of the experiment on plant growth, it was found that the mass germination of plants is much more effective with peat with the addition of sediment than with pure peat.

As a result of the experiment, it was found that the growth indices of plants growing with the addition of sewage sludge after pyrolysis at a temperature of 400 °C are higher on the soil than the growth indices of plants growing on soil with the addition of peat after pyrolysis at 800 °C and after dehydration at a temperature of 130 °C.

Thus, the quality of the soil with the addition of sewage sludge after pyrolysis at a temperature of 400 °C can be considered better in comparison with other studied samples.

2.2.3. Experiment to determine toxicity by mortality test - object of Daphnia magna Straus in laboratory conditions. For biotesting according to PND FT 14.1:2:3:4.12–06 “Toxicological control methods. Methodology for measuring the amount of Daphnia magna Straus to determine the toxicity of drinking, fresh natural and waste water, water extracts from soils, soils, sewage sludge, production and consumption waste by the direct counting method (edition 2014)” [3] a preliminary sample of sewage sludge, are prepared for biotesting by preparing the extract, and then diluting: 10, 100 1000 and 10000 times.

The average lethal multiplicity of dilution of water, water extracts of sewage sludge is less than 0.99 % of test objects for a 48 - hour exposure. Accordingly, this is a harmless multiplicity of dilutions of the aqueous extract, causing the death of no more than 10 % of test objects for a 48-hour exposure. Thus, it was established that the entire studied wastewater sludge extract with no dead test objects in 48 hours, LKR50,48 = 10 (dilution factor of 1, 10, 100, 1000 and 10000 times). Thus, it was determined that the hazard class of sewage sludge from wastewater treatment plants is 5. It was found that as a result of chemical analysis, the quality of the soil, with the addition of sewage sludge after pyrolysis at a temperature of 400 °C, can be considered better than other samples studied. Sewage sludge after treatment with low-temperature pyrolysis (400 °C) fully corresponds to agrochemical indicators, and therefore can be used in the production of agricultural fertilizers. As a result of biotesting measurements of the amount of Daphnia magna Straus to determine the toxicity, sewage sludge from wastewater treatment plants does not have a toxic effect.

3. Technical solution for the use of sewage sludge

When choosing a mixing of fertilizers, ammonium nitrate NH₄NO₃, urea (NH₂) 2CO, double superphosphate and potassium chloride are taken as the basis, consider the actual value and the value according to the literature data, in the calculation we will consider the average value of the elements indicated in table 16. In this work, the most acceptable fertilizer is selected it is balanced when the ratio of N, P₂O₅ and K₂O is the same, therefore, we select 5% of active elements for 600 g of ash, that is, we strive to approach the patent No. RU 2704292 C2 “Mineral fertilizer” taken as a basis, since the already proven method with a similar ratio of components they have good results [7].

The chemical analysis of sewage sludge obtained the following results: P₂O₅ - 1.5%; N/ammonium – 1.12%.

When calculating 700 g of sewage sludge, it turns out 1.5% -10.5 g of P₂O₅; 1.12% - 7.84 g N [5].

If we take sewage sludge, carbamide, double superphosphate and potassium chloride, then we take the ratio indicated in table 6.
Table 6. Estimated amount of nutrients in fertilizer.

| Fertilizer name          | Component | Calculated value, % | Actual value, % | Accepted for calculation, % |
|--------------------------|-----------|---------------------|-----------------|----------------------------|
| Ammonium nitrate NH₄NO₃ | N         | 35                  | 32-35           | 34                         |
| Urea (NH₂)₂CO            | N         | 43                  | 46              | 46                         |
| Double superphosphate    | P₂O₅      | 51,8                | 40-52           | 46                         |
| Potassium chloride       | K₂O       | 63,1                | 50-62           | 56                         |

If we take sewage sludge, ammonium nitrate, double superphosphate and potassium chloride, then we take the ratio indicated in table 7.

Table 7. Estimated amount of the component composition of fertilizer with ammonium nitrate.

| Fertilizer name          | Component | Proposition in patent value | Percentage calculation | Calculated value | Average value | Average value of the content of the basic substance |
|--------------------------|-----------|----------------------------|------------------------|-----------------|---------------|----------------------------------|
| Sewage sludge            | C         | 700 g                      | 100 %                  | 700 g           | 700 g         | 85 %                              |
| Ammonium nitrate NH₄NO₃  | N         | 125 g                      | 34 %                   | 50.34 g         | 50 g          | 5 %                               |
| Double superphosphate    | P₂O₅      | 95 g                       | 46 %                   | 49.6 g          | 50 g          | 5 %                               |
| Potassium chloride       | K₂O       | 90 g                       | 56 %                   | 50.4 g          | 50 g          | 5 %                               |

If carbamide is taken instead of ammonium nitrate, a carbonated dry residue is obtained and we take the ratio indicated in table 8.

Table 8. Estimated amount of the component composition of the fertilizer with urea.

| Fertilizer name          | Component | Proposition in patent value | Percentage calculation | Calculated value | Average value | Average value of the content of the basic substance |
|--------------------------|-----------|----------------------------|------------------------|-----------------|---------------|----------------------------------|
| Sewage sludge            | C         | 700 g                      | 100 %                  | 700 g           | 700 g         | 85 %                              |
| Urea (NH₂)₂CO            | N         | 90 g                       | 46 %                   | 49.6 g          | 50 g          | 5 %                               |
| Double superphosphate    | P₂O₅      | 95 g                       | 46 %                   | 52.4 g          | 50 g          | 5 %                               |
| Potassium chloride       | K₂O       | 90 g                       | 56 %                   | 50.4 g          | 50 g          | 5 %                               |

The mixing ratios selected in tables 7 and 8 are considered the most suitable balanced fertilizer.

It is also known that a fertilizer for feeding garden roses taken as a prototype [7] contains mineral components, which are used as ash from solid fuel boilers, double superphosphate, ammonium nitrate, copper sulfate and potassium sulfate with the following ratio of components, wt. % is shown in 9.
Table 9. Component content of fertilizers.

| Fertilizer (component) | Percentage |
|------------------------|------------|
| Double superphosphate  | 7,0 – 9,0  |
| Copper sulfate         | 3,0 – 5,0  |
| Ammonium nitrate       | 5,0 – 7,0  |
| Potassium sulfate      | 5,0 – 7,0  |
| Boiler ash             | Rest       |

The task is achieved through the use in the production of mineral fertilizers as the main raw material component, which is different in its qualities from the ash of solid fuel boilers - the ash of treatment facilities obtained by burning the sludge of primary sedimentation tanks and excess activated sludge formed during the treatment of wastewater from urban wastewater treatment plants. The task is achieved by a fertilizer containing the products of treatment of wastewater treatment plants, potassium and a phosphorus derivative, while, as products of processing of treatment facilities, it contains ash obtained during the incineration of sludge formed during the treatment of wastewater at treatment facilities with the following ratio of components indicated in table 10.

Table 10. Fertilizer composition.

| Fertilizer (component)          | Content   |
|---------------------------------|-----------|
| ash from incineration of sewage | 700 g     |
| ammonium nitrate (carbamide)   | 50 g      |
| double superphosphate           | 50 g      |
| potassium chloride              | 50 g      |

The claimed technical solution is relevant for the domestic economy, since the volume of production is increased due to the use of ash sludge obtained in the process of wastewater treatment of urban wastewater treatment plants, i.e. the offer is "industrially acceptable".

The production of mineral fertilizers is carried out using an installation that includes a unit for receiving and preparing ash and mineral additives.

Ash and mineral additives are delivered by road, weighed on a truck scale (not shown in the figure) and then fed to silo 1, equipped with bag filters 2.

Ash from silos 1 through the aeration system of silos 16 and shut-off gates (batchers) 3 is fed to the installation of pneumatic and magnetic separation. With the help of screw feeders 4, ingredients (ash, mineral additives) are fed to a common screw conveyor 6 with a split pen 17, which directs their mixture to a mixer 5, from where the mixture can go either to a granulator or to a conveyor 6, which directs the mixture or granules through the elevator 7 into the screw conveyor 8, which loads the silos with the mixture or granules and through the shut-off gates 3 and the installation 9 packs the bags. The other part of the mixture through the sluice gate 10, the drum sieve 11 and the filling machine 12 goes to storage or transportation. The dust of the mixture is fed with the help of compressed air from the compressor unit 15 from the filling machine to the bag filter 13, designed to remove gases using the fan 14 and for loading into the filling machine 12.

To reduce sticking and improve the flow of materials, all silos are equipped with aeration systems. Compressed, moisture-free air is supplied for aeration from the compressor room.

To clean the dusty air leaving the silos, a pressure bag filter is installed on each of them.

The production of mineral fertilizers is carried out using an installation including a unit for receiving and preparing ash and mineral additives [6]. The functional diagram of the installation is shown in figure 3.
After the pyrolysis unit UTD - 2, the coke enters the metal silo, where it is further mixed with ammonium nitrate (carbamide), double superphosphate and potassium chloride. Then it goes to packaging.

**Figure 3.** Functional diagram of the installation: 1 – metal silo; 2 – bag filter; 3 – shut-off gate; 4 – screw feeder; 5 – screw conveyor with a split blade; 6 – mixer; 7 – compressor installation for air purification; 8 – pyrolysis unit; 9 – silo aeration system.

4. **Conclusions**
As a result of the qualitative and quantitative analysis of sewage sludge from the treatment facilities of PJSC “Togliattiazot”, the gross content of mercury, acid-soluble forms of lead, cadmium, manganese, copper, nickel, chromium, zinc, gross arsenic content, mass fraction of moisture, organic matter, pH of water was determined. Hoods, all indicators fully comply with the requirements of SanPiN 2.1.7.573-96 and GOST R 17.4.3.07-2001.

For laboratory tests, a physical model of a pyrolysis installation was created on the basis of the laboratories of Togliatti State University.

A number of chemical studies of sewage sludge after pyrolysis at a temperature of 800 °C and 400 °C and thermal drying at a temperature of 1300°C were carried out for compliance with agrochemical indicators according to SanPiN 2.1.7.573-96 and GOST R 17.4.3.07-2001, including: N nitrogen (according to Keldahl), mass fraction of moisture, mass for organic matter, pH of the water extract (pH), mass fraction of total phosphorus P₂O₅, which made it possible to draw a conclusion about the advisability of using sewage sludge after the pyrolysis process at a temperature of 400 °C. As a result of the experiment on plant growth, it was found that the mass germination of plants is much more effective with peat with the addition of sewage sludge obtained after the pyrolysis process (T = 400°C) than with pure peat.
It has been experimentally established that the growth rates of plants grown with the addition of sewage sludge after pyrolysis at a temperature of 400 °C are higher on the soil than the growth rates of plants grown on soil with the addition of peat after pyrolysis at 800 °C and after dehydration at a temperature of 130 °C. The hazard class of sewage sludge from the treatment facilities of PJSC “Togliattiazot” is fifth. It was found that, as a result of chemical analysis, the quality of the soil, with the addition of sewage sludge after pyrolysis at a temperature of 400 °C, can be considered better in comparison with other studied samples. Sewage sludge after treatment with low-temperature pyrolysis (400 °C) fully corresponds to agrochemical indicators, and therefore can be used in the production of agricultural fertilizers. As a result of biotesting measurements of the amount of Daphnia magna Straus to determine the toxicity, the wastewater sludge from the treatment facilities of PJSC “Togliattiazot” does not have a toxic effect. A method of preparation before using sewage sludge as obtaining fertilizers for agricultural purposes is proposed and substantiated, namely, the use of a batch-type pyrolysis unit of the loading type UTD-2.

The calculation of the optimal ratio of obtaining mineral fertilizers by mixing the following mixture ingredients: sewage sludge (C) 700 g, ammonium nitrate NH₄NO₃ (N) 50 g or carbamide (NH₂) 2CO (N) 50 g, double superphosphate (P₂O₅) 50 g, potassium chloride (K₂O) 50 g.

The proposals make it possible to increase the production of mineral fertilizers and reduce the accumulation of sewage sludge in the sludge fields of treatment facilities at industrial enterprises.

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