SECTION 5. GENERAL AGRICULTURE

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5.1 Change in the humus state of aluvisol due to implementation of sediment of sewage sludge under the energy willow

In modern conditions, energy willow is considered as a promising crop for use in bioenergy, which serves as a reliable source of biomass and the formation of sustainable bioenergy phytocenoses.

As a rule, such phytocenoses are formed on marginal, degraded, low-value soils, which are characterized by a low level of effective fertility and are not occupied by food crops.

One of the ways to increase the bioproductivity of such soils is the introduction of sewage sludge, which is characterized by a high content of nutrients, in particular macro- and microelements, as well as organic matter, which participates in biogeochemical transformations and is a factor in increasing the energy status of the soil system.

The purpose of our research was to determine the degree of influence of the use of sewage sludge and composts based on it on the change in the content of humic compounds of the soil, introduced under the energy willow.

Before starting the field experiment, three types of compost were also produced:

1. Compost (SS + sawdust (3:1));
2. Compost (SS + straw (3:1));
3. Compost (SS+ straw (3:1) + cement dust 10%).

The main agrochemical indicators were determined in each of the options of manufactured composts [323, 331 – 333].

Field studies to determine the agrochemical efficiency of sewage sludge for growing energy willow on the sod-podzolic soils of Precarpathia were carried out according to the following scheme:

1. Control – without fertilizers; 2. Mineral fertilizers - $N_{100}P_{100}K_{100}$; 3. SS - 40 t/ha; 4. SS - 60 t/ha; 5. SS - 80 t/ha; 6. Compost (SS + sawdust (3:1)) – 60 t/ha; 7. Compost (SS + straw (3:1)) – 20 t/ha; 8. Compost (SS + straw (3:1)) – 40 t/ha; 9. Compost (SS + straw (3:1)) – 60 t/ha; 10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha. Planting scheme of energy willow – 0.33 x 0.70 m. Plot width 4.0 m; length – 7 m; area - 28 m^2. Repetition - three times, placement of plots - systematic.

Energy willow (Salix winimalis L.) is one of the fastest-growing types of tree crops in terms of length (growth of shoots in one day can reach 3-5 cm) and vegetative mass. The willow bred selectively for energy purposes is planted with seedlings 20 – 25 cm long. Before planting, the seedlings were soaked in water for 24 – 48 hours, which contributed to temperature adaptation on the one hand, and on the other hand, the seedlings during this period accumulated such an amount of water that they were able to grow without watering after planting in the soil [333, 341 – 343].

Transplanting into the soil was carried out in early spring, immediately after frost. At this time, soil moisture is the highest. Seedlings were transplanted into the soil manually. The plot was plowed in advance and cleared of weeds. Fertilizers were applied according to the options according to the scheme of the experiment. Planting scheme – 33 cm x 70 cm. Seedlings were planted in such a way that two to three buds remained above ground level.

2-3 weeks after transplanting the plants into the soil, the first new shoots appeared. During the first year, careful care and protection against weeds was provided, since the willow is unable to develop a sufficiently powerful root system at the initial stages of organogenesis due to fast-growing weeds. In the first months, special attention was paid to the destruction of weeds, until the branches of the willow plants are covered by the weeds. In the first 3 – 4 months, weeds were destroyed by hand. Later, when the willow outgrew the weeds, the process of killing weeds was no longer a determining factor in care, and during dry periods weeding was not carried out, thereby preventing excessive drying of the soil.

The work carried out in the first year in an appropriate manner to ensure the vital activity of plants determines the level of accumulation of vegetative mass in the following years. In the first year of planting, energy willow undergoes the formation and development of the root system. From one seedling, 2-5 branches with a length of about 2 – 4 m sprout. The length of the branches depends on the water regime and the level of mineral nutrition. From the economic point of view, the most suitable for use is the biomass of three to four or more years of energy willow. The three-year-old willow was cut by hand and weighed to analyze the productivity of the raw mass. After drying to a constant mass, the biomass of dry matter was determined and samples were taken for laboratory analysis.

Sampling for agrochemical analyzes was carried out in accordance with DSTU 4287 [318, 322]. Determination of the humus content in the soil was carried out according to the Tyurin method according to DSTU 4289 [349, 353]; labile forms - after each crop rotation rotation according to DSTU 4732 [355, 361]. The fractional and group composition of humus was determined by the method of Ponomaryova – Plotnikova. [352, 360]. The selection of soil samples for physical and chemical analyzes was carried out in accordance with DSTU ISO 11464 [323, 327 – 331]. Determination of pH was carried out according to DSTU ISO 10390 [333, 335, 339], determination of hydrolytic acidity according to the Kappen method [347 – 350]. Processing and generalization of the research results was carried out using the methods of mathematical statistics with the help of the STATISTICA 6.0 and EXEL programs

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Dynamics of the content of humic substances in the soil. The amount of organic matter in the soil determines the level of its fertility. All factors of soil fertility are closely related and interdependent. Physical properties, structure, thermal and water properties, porosity, biological activity, nutrient regime and absorption capacity of soils, etc. depend on the content of organic matter [338, 339, 362]. Measures to increase soil fertility and crop yields are closely related to the creation of a stable, deficit-free balance of humus in the soil [327, 333, 337 – 341, 345, 355]. It has been proven that the fertilization of the soil by organic matter contributes to the activation of the processes of transformation of organic substances. It has been established that SS have a positive effect on the fixation of humic substances in podzolized chernozem, which is indicated by an increase in the content of the 1st and 2nd fractions of humic acids. After the introduction of SS, an increase in the content of total organic matter, as well as its labile and water-soluble forms, is noted [343].

In our research, the content of organic matter in the profile of sod-podzolic soil changed significantly under the influence of fertilizer application, including the application of SS (Fig. 1.1).

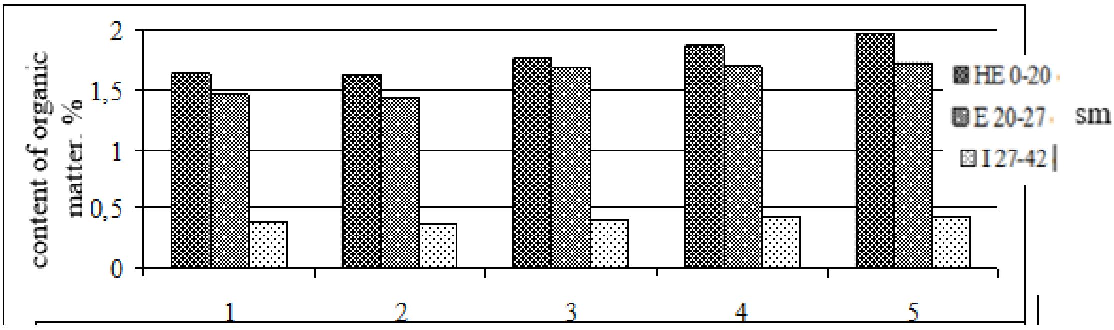

Figure 1. Dynamics of the content of organic matter in the profile of sod-podzolic soil under the influence of repeated application of sewage sludge (2016 - 2019):

1. Control – without fertilizers; 2. Mineral fertilizers – $N_{100}P_{100}K_{100}$; 3. SS – 40 t/ha; 4. SS – 60 t/ha; 5. SS – 80 t/ha.

In the control variant, the content of organic matter in the 0 – 20 cm soil layer was 1.64%. In the eluvial horizon, this indicator was 1.46%, and in the eluvial horizon at a depth of up to 42 cm – 0.38%. The application of mineral fertilizers contributed to a decrease in the content of humus in the humus-eluvial horizon by 0.02% compared to the option without the application of fertilizers. In the eluvial and illuvial horizons, the humus content was 1.44 and 0.37%, respectively.

The application of SS provided a significant increase in the content of humus in the humus-eluvial horizon. In particular, when it was applied at a dose of 40 t/ha, the humus content was 1.76% in the upper humus-eluvial horizon and decreased with depth to 0.4% in the 27 – 42 cm layer. of humus at a depth of 0 – 20 cm was 1.88 – 1.97% and decreased to 0.43% with depth.

When applying 60 t/ha of compost based on SS and straw, the humus content was 1.70% in the upper humus-eluvial horizon of the sod-podzolic soil (Fig. 2).

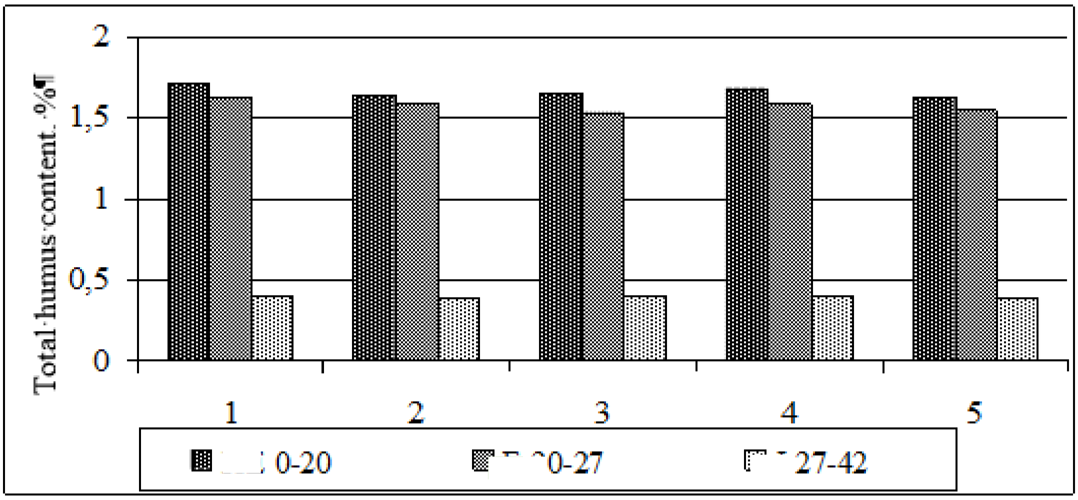

Figure 2. Dynamics of humus content in the profile of sod-podzolic soil under the influence of repeated application of composts based on sewage sludge (2016 – 2019):

1. Control – without fertilizers; 2. Compost (SS + sawdust (3:1)) – 60 t/ha; 3. Compost (SS + straw (3:1)) – 20 t/ha; 4. Compost (SS + straw (3:1)) – 40 t/ha; 5. Compost (SS + straw (3:1)) – 60 t/ha

A decrease in humus content to 0.40% was observed in the illuvial horizon. However, this rate was higher compared to the control without fertilizers at the same depth. When applying compost based on SS and straw at a dose of 20 and 40 t/ha, respectively, the humus content decreased compared to the areas where fresh sediment was applied and fluctuated slightly within the range of 1.64–1.65% at a depth of 0–20 cm. application of compost based on SS and straw at a dose of 60 t/ha, the humus content decreased from 1.7 to 0.4% in the 0 – 42 cm layer. Humus content indicators in this variant increased due to the application of a larger dose of compost. With the introduction of compost with a mineral filler in option 10 (compost based on SS + straw (3:1) + cement dust 10% at a dose of 40 t/ha), the humus content decreased to 1.7% in the humus-eluvial horizon, compared to the options , where fresh SS was introduced, and decreases down the profile to 0.4% in the illuvial horizon (Table 1.).

Table 1.

Dynamics of the content of labile and stable forms of humus during repeated application of sewage sludge at a depth of 0 – 20 cm (2016 – 2019), %

option	Humus is active	Humus is	General humus	Humus is active/
1. Control – without fertilizers	0,64	1,00	1,64	39
2. $N_{100}P_{100}K_{100}$	0,63	1,02	1,65	38
3. SS – 40 t/ha	0,64	1,01	1,66	37
4. SS – 60 t/ha	0,65	1,05	1,70	38
5. SS – 80 t/ha	0,62	1,12	1,74	37
6. Compost (SS + sawdust (3:1)) – 60 t/ha	0,60	1,10	1,70	35
7. Compost (SS + straw (3:1)) – 20 t/ha	0,61	1,05	1,66	36
8. Compost (SS + straw (3:1)) – 40 t/ha	0,61	1,08	1,69	36
9. Compost (SS + straw (3:1)) – 60 t/ha	0,62	1,08	1,70	36
10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha.	0,61	1,01	1,67	36
Least Significant Difference 0,5	0,1	0,02		

Comparing the option where compost based on SS and straw (3:1) was applied at a dose of 40 t/ha and the same amount of compost only with the addition of 10% cement dust, the content of active humus remained at the level of 0.6%, but the content of cement dust contributed reduction of passive humus by 0.07%, respectively, and the content of total humus also decreases by 0.02% compared to the application of SS + straw - 40 t/ha.

Active humus is the nearest reserve of nutrient elements for plants, is a factor in the formation of agronomically valuable aggregates of the soil structure [321, 329 – 351, 362]. The results of determination of active (labile) humus showed that its content increased when SS was applied as a fertilizer. The highest indicators of the content of labile humus were observed in the variants where the highest doses of organic fertilizers were applied. It is worth noting that in almost all versions of the experiment, the content of labile humus in the upper layer ranged from 0.61 to 0.64%.

Passive or stable humus is a part of organic colloids of a humus nature that has undergone "aging" and is firmly held by physical and chemical forces on the surface of finely dispersed soil particles [317, 331]. In contrast to the indicators of the content of labile humus, the indicators of passive (stable) humus increased with the application of SS. When it is applied in a dose of 40 t/ha, the content of passive humus is 1.07%. As the dose increased, the content of passive humus also increased to 1.1% (Table 2).

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Table 2

Dynamics of the content of labile and stable forms of humus during repeated application of sewage sludge at a depth of 20-40 cm (2016 – 2019), %

option	Humus is active	Humus is passive	General humus	Humus is active/ general humus
1. Control – without fertilizers	0,48	0,98	1,46	32
2. $N_{100}P_{100}K_{100}$	0,45	1,00	1,45	31
3. SS – 40 t/ha	0,49	1,08	1,57	31
4. SS – 60 t/ha	0,51	1,12	1,63	31
5. SS – 80 t/ha	0,52	1,17	1,69	30

Continuation of the Table 2

6. Compost (SS + sawdust (3:1)) – 60 t/ha	0,51	1,18	1,69	30
7. Compost (SS + straw (3:1)) – 20 t/ha	0,55	1,06	1,61	31
8. Compost (SS + straw (3:1)) – 40 t/ha	0,53	1,17	1,70	30
9. Compost (SS + straw (3:1)) – 60 t/ha	0,52	1,18	1,70	30
10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha.	0,53	1,15	1,68	31
Least Significant Difference 0,5	0,02	0,01		

In particular, in the upper (0 – 20 cm) and lower (20 – 40 cm) layers of the soil, the proportion of stable humus in the control without fertilizers was 61-68%.

With the introduction of mineral fertilizers $N_{100}P_{100}K_{100}$, the proportion of stable humus increased by 1% in the upper and lower layers. The introduction of SS ensured a further increase in the share of stable humus to 68-70%.

The patterns of stabilization of the humus state of the soil can be described by the following linear regression equations (Fig. 3, Fig. 4):

– for a layer (0-20 cm) of soil:

$$y = 0{,}4\,x + 61{,}4\ (R^2 = 0{,}80), \tag{1}$$

– for a layer (20 – 40 cm) of soil:

$$y = 0{,}2364\,x + 68\ (R^2 = 0{,}57); \tag{2}$$

where *y* is the share of stable humus in the total humus content, %;
x – application dose of SS, t/ha.
The multiple coefficients of determination indicate a high level of closeness of the connection between the introduced SS and the growth of the share of stable humus in the soil. At the same time, despite the use of high doses of SS, the intensity of humus accumulation changed insignificantly [353].

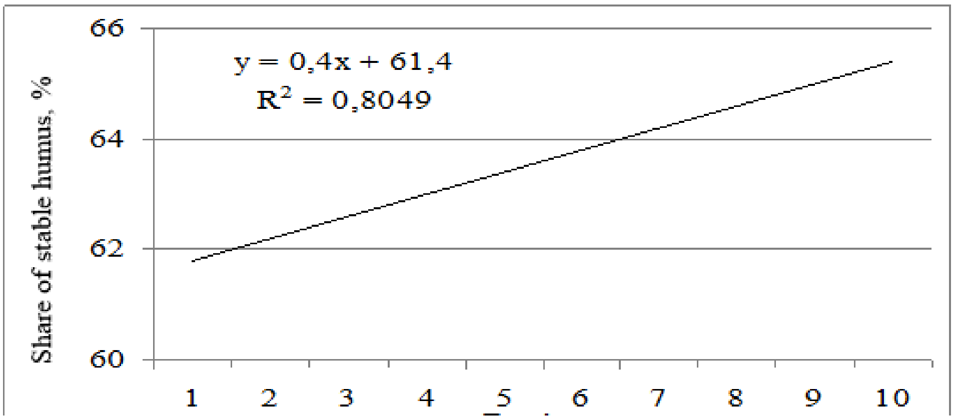

Figure 3. Change in the share of stable humus in the soil at a depth of 0 – 20 cm, depending on the dose of re-application of sewage sludge and composts based on it, 2016 – 2019:

1. Control – without fertilizers; 2. Mineral fertilizers - $N_{100}P_{100}K_{100}$; 3. SS - 40 t/ha; 4. SS - 60 t/ha; 5. SS - 80 t/ha; 6. Compost (SS + sawdust (3:1)) – 60 t/ha; 7. Compost (SS + straw (3:1)) – 20 t/ha; 8. Compost (SS + straw (3:1)) – 40 t/ha; 9. Compost (SS + straw (3:1)) – 60 t/ha; 10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha.

Therefore, the content of active humus in the sod-podzolic soil decreased with the application of fresh SS, while the content of passive humus increased.

With the introduction of composts based on SS, the content of passive humus decreased compared to the options where fresh SS was applied, but remained higher compared to the control without fertilizers. The proportion of humic acids in the humus increases with the introduction of fresh SS.

Change in the fractional and group composition of humus due to the introduction of sewage sludge

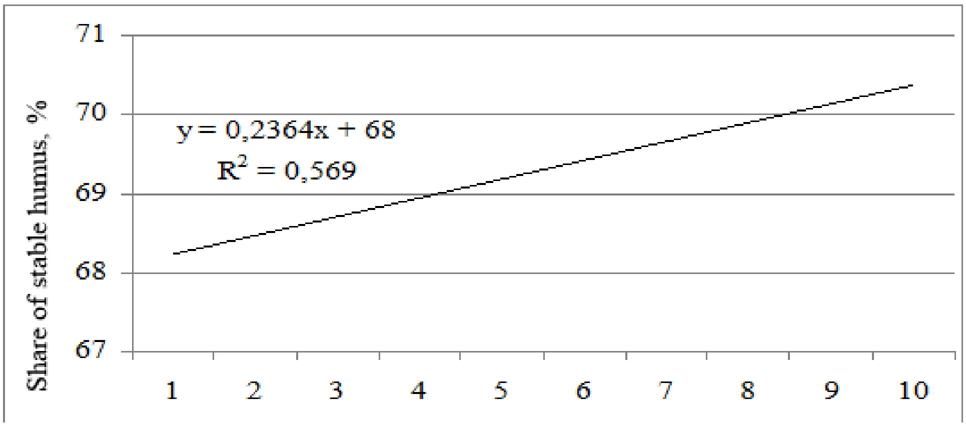

Figure 4. Change in the share of stable humus in the soil at a depth of 20 – 40 cm, depending on the dose of re-application of sewage sludge and composts based on it, 2016 – 2019:

1. Control – without fertilizers; 2. Mineral fertilizers - $N_{100}P_{100}K_{100}$; 3. SS - 40 t/ha; 4. SS - 60 t/ha; 5. SS - 80 t/ha; 6. Compost (SS + sawdust (3:1)) – 60 t/ha; 7. Compost (SS + straw (3:1)) – 20 t/ha; 8. Compost (SS + straw (3:1)) – 40 t/ha; 9. Compost (SS + straw (3:1)) – 60 t/ha; 10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha.

An analytical review of the literature on the influence of fertilizer on the fractional-group composition of humus indicates that the long-term use of manure and mineral fertilizers increases the content of humic and fulvic acid groups in the soil and reduces the content of unhydrolyzed residue compared to unfertilized areas [334, 335, 338, 368]. It is worth noting that in the scientific literature there are very few reports on the dynamics of the fractional-group composition of turf-podzolic soil under the influence of the introduction of SS [328, 367].

The sod-podzolic soil of the experimental site was marked by an increase in the humus content in the HE horizon from 1.66 to 1.74% (Table 3).

In the control without fertilizers, the content of humic acids was 0.22% or 17.0% of the total amount of organic carbon in the 0 – 20 cm layer. The use of a mineral fertilizer system increased the absolute value of humic acids to 0.24%.

However, relative to total organic carbon, the percentage was at the level of 19.5%. The content of the fraction of humic acids, which are bound to Ca^{2+}, was at the level of 0.11% of the total content of humus. With an increase in the dose of organic fertilizers based on SS, their content increased. However, the highest percentage of 0.15% was noted for the application of SS at a dose of 80 t/ha. The content of fulvic acids in humus also depended on applied fertilizers. With the introduction of SS in a dose of 40 – 80 t/ha, the proportion of humic acids increased and the proportion of fulvic acids decreased.

Under the conditions of the experiment, the content of the insoluble residue in the humus changed significantly. In particular, in the control without fertilizers, it was 0.6%. Mineral organic fertilizers contributed to a gradual increase in the content of insoluble residue in humus from 0.8 – 0.9% of soil weight or 46.9 – 56.5% to total carbon. The content of insoluble residue increased in the variants where composts based on SS were used in the range of 0.7 – 0.8% by weight of the soil, or 48.4 - 59.7% by total organic carbon. The ratio of humic acids to fulvic acids shows the orientation of organic matter mineralization processes and serves as an indicator of the humic state of the soil [327]. Under the conditions of the experiment, the ratio of humic acids to fulvic acids in the upper (0 – 20 cm) layer of the soil varied within 0.6 – 0.9%.

Analyzing the data on the content of humus in the subsoil layer, it should be noted a similar trend that we established in the arable layer 0 – 20 cm, however, in the humus of the subsoil layer, the proportion of humic acids decreased and the proportion of fulvic acids increased (Table 4). The content of insoluble residue in the options where composts based on SS were used remained within 0.52 – 0.54% of the soil weight, or 53.2 – 55.0% of the total organic carbon. The content of insoluble humus residue compared to the upper layer was slightly higher, which indicates a certain stabilization of humus in the subsoil layer. However, this ratio remained the same for all options except the control one [329, 341 – 343].

Table 3. Fractional and group composition of soil humus in the 0-20 cm layer after repeated introduction of SS under energy willow, on average for 2016-2019, %

Option	General humus	C is organic	C is organic						
			Soluble					Insoluble residue	Humic acids / Fulvic acids
			In total	Humic acids			Fulvic acids		
				In total	Free and bound with	Connected with			
1. Control – without fertilizers	1,64	1,16 100	0,56 41,6	0,22 17,0	0,12 9,8	0,10 7,2	0,34 24,6	0,60 58,4	0,6
2. $N_{100}P_{100}K_{100}$	1,65	1,36 100	0,57 53,1	0,24 19,5	0,13 10,6	0,11 8,9	0,33 33,6	0,79 46,9	0,7
3. SS – 40 t/ha	1,66	1,33 100	0,55 49,1	0,25 19,0	0,13 10,1	0,12 8,9	0,30 30,1	0,78 50,9	0,8
4. SS – 60 t/ha	1,70	1,37 100	0,55 52,3	0,27 18,9	0,14 10,2	0,13 8,7	0,28 33,4	0,82 47,7	0,8
5. SS – 80 t/ha	1,74	1,54 100	0,58 43,5	0,31 20,5	0,16 10,7	0,15 9,8	0,27 23,0	0,87 56,5	0,9
6. Compost (SS + sawdust (3:1)) – 60 t/ha	1,70	1,34 100	0,54 40,3	0,25 18,7	0,14 10,2	0,11 8,5	0,29 21,6	0,79 59,7	0,9
7. Compost (SS + straw (3:1)) – 20 t/ha	1,66	1,25 100	0,53 50,5	0,25 17,7	0,14 9,8	0,11 7,9	0,28 32,8	0,72 49,5	0,8
8. Compost (SS + straw (3:1)) – 40 t/ha	1,69	1,30 100	0,54 51,6	0,28 19,0	0,16 10,1	0,12 8,9	0,26 32,6	0,76 48,4	0,8
9. Compost (SS + straw (3:1)) – 60 t/ha	1,70	1,35 100	0,55 40,2	0,30 18,7	0,17 10,2	0,13 8,5	0,25 21,5	0,80 59,8	0,9
10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha.	1,67	1,30 100	0,51 41,0	0,23 18,2	0,13 10,1	0,10 8,1	0,28 22,8	0,79 59,0	0,9

Note. Above the line - % to the weight of the soil; under the line - % to the total organic carbon of the soil.

Table 4. Fractional and group composition of humus of tree-podzolic soil in a layer of 20-40 cm after repeated application of SS under energy willow, average for 2016-2019, %

Option	General humus	C is organic	C is organic							Humic acids / Fulvic acids In total
			Soluble						Insoluble residue	
			In total	Humic acids			Fulvic acids			
				In total	Free and bound with R_2O_3	Connected with calcium				
1. Control – without fertilizers	1,45	1,02 100	0,42 45,9	0,09 12,1	0,08 9,9	0,01 2,2	0,33 33,8		0,60 54,1	0,3
2. $N_{100}P_{100}K_{100}$	1,44	1,11 100	0,48 43,0	0,14 12,6	0,11 9,8	0,03 2,8	0,34 30,4		0,63 57,0	0,4
3. SS – 40 t/ha	1,56	1,04 100	0,45 46,3	0,12 12,7	0,10 10,1	0,02 2,6	0,34 33,6		0,58 53,7	0,4
4. SS – 60 t/ha	1,62	1,07 100	0,46 44,8	0,13 12,7	0,10 9,9	0,03 2,8	0,33 32,1		0,61 55,2	0,4
5. SS – 80 t/ha	1,68	1,10 100	0,49 43,7	0,15 13,3	0,11 9,8	0,04 3,5	0,32 30,4		0,63 56,3	0,4
6. Compost (SS + sawdust (3:1)) – 60 t/ha	1,68	1,01 100	0,47 46,8	0,14 13,4	0,11 10,6	0,03 2,8	0,34 33,4		0,54 53,2	0,4
7. Compost (SS + straw (3:1)) – 20 t/ha	1,60	0,99 100	0,46 45,9	0,12 12,5	0,10 9,9	0,02 2,6	0,35 33,4		0,52 54,1	0,4
8. Compost (SS + straw (3:1)) – 40 t/ha	1,69	0,98 100	0,46 46,1	0,12 12,7	0,10 10,1	0,02 2,6	0,33 33,4		0,53 53,9	0,4
9. Compost (SS + straw (3:1)) – 60 t/ha	1,69	1,02 100	0,48 45,7	0,14 12,6	0,11 9,8	0,03 2,8	0,34 33,1		0,54 54,3	0,4
10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha.	1,67	1,00 100	0,46 45,0	0,13 13,2	0,11 10,6	0,02 2,6	0,33 31,8		0,54 55,0	0,4

Note. Above the line - % to the weight of the soil; under the line - % to the total organic carbon of the soil.

In general, indicators of the fractional-group composition of humus indicate that without fertilization, the humus condition of sod-podzolic soil deteriorates. Mineral fertilizers $N_{100}P_{100}K_{100}$ partially stopped the degradation processes, but contributed to an increase in the proportion of fulvic acids in humus compared to the options where SS and composts were applied.

Under the conditions of the experiment, the use of SS and composts based on it ensured a qualitative improvement in the fractional-group composition of humus. With the application of SS 80 t/ha and compost – SS + sawdust (3 : 1) – 60 t/ha in the upper horizons of sod-podzolic soil, the content of total humus was 2.64 and 2.31%, respectively, which compared to the control without of fertilizers was higher by 0.8%.
Change in the energy content of humus due to the introduction of sewage sludge

Issues of bioenergetics and energy of soil formation are gaining more and more relevance in our time, which is related to both general environmental problems and specific practical tasks of preserving and restoring soil fertility [327, 340]. In connection with this, there is a need for scientific substantiation of measures to strengthen the factor of attraction of organic matter into the soil through the introduction of organic matter. SS is characterized by a high content of organic matter and nutrients, a wide range of macro- and microelements, and its introduction into the soil helps to increase the content of humus [318 – 321, 344]. The energy capacity of soils depends on the content of humus and its calorific value, in addition, these indicators testify to the potential fertility of soils, since the productivity of soils is higher, the more energy they contain associated with humus [332 – 336].

Fractional-group distribution of energy makes it possible to determine the participation of each fraction of humic substances in the formation of the total energy capacity of the soil and to more deeply investigate the redistribution of energy resources of organic matter [317, 347]. The heat-generating capacity of organic matter is formed due to the fractional-group structure of humic substances. It is evidence of the quality of energy connections and biotic activity of the soil [362, 365].

When determining the energy state of the soil, the fractional-group composition of humus, the heat-generating capacity of humus, as well as its agrophysical state, which changed under the influence of fertilizer, were taken into account [367]. In the calculation, the equation of O. Orlov [335] was used, which allows taking into account the qualitative composition of humus and the content of its main fractions. The calculations indicate significant differences in the indicators of the accumulation of energy reserves by soil humus under the influence of the use of SS as an organic fertilizer for energy willow (Table 5) [340 – 342, 351 – 353]. Under the influence of the mineral fertilizer system in the upper (0 – 20 cm) soil layer, the humus content did not increase, but the energy reserves in the humus in the upper and lower soil layers increased by 5.9 and 6.0 GJ/ha, respectively, compared to the control variant.The application of SS ensured the accumulation of humic compounds in the soil and the increase in the proportion of humic acids and non-hydrolyzed residues, which are characterized by the highest heat capacity, and this contributed to the growth of energy reserves in humus. With an increase in the proportion of SS, the energy content of humus increased, both in the arable and subsoil layers of the soil [346 – 349, 357 – 360]. Under the influence of fertilizer based on compost from SS + sawdust (3 : 1), an increase in energy reserves in humus was observed by 0.9 GJ/ha in the upper (0 – 20 cm) and by 0.7 GJ/ha in the lower (20 – 40 cm) in the soil layers compared to the control without fertilizers. With an increase in the dose of compost, the energy content of humus increased. The highest indicators of gross energy reserves were noted for SS at a dose of 80 t/ha and compost (SS + sawdust (3 : 1)) – 60 t/ha with the highest content of fresh SS. In these variants, the energy intensity indicator was at the level of 6.3 and 5.5 GJ/ha, respectively, in the upper and lower layers of the soil [343 – 345, 356 – 358]..

Table 5

The energy content of humus of sod-podzolic soil under different fertilizing systems of energy willow, average for 2016 – 2019, GJ/ha

1. Control – without fertilizers 2. $N_{100}P_{100}K_{100}$	Heat-generating capacity of humus	Groups of humic substances			Energy reserves accumulated by humus
		∑ Humic acids	∑ Fulvic acids	huminy	
1. Control – without fertilizers	0,18 / 0,15	0,22 / 0,09	0,34 / 0,33	0,60 / 0,60	4,56 / 4,79
2. $N_{100}P_{100}K_{100}$	0,22 / 0,17	0,24 / 0,14	0,33 / 0,34	0,79 / 0,63	5,92 / 5,98
3. SS – 40 t/ha	0,21 / 0,16	0,25 / 0,12	0,30 / 0,34	0,78 / 0,58	5,50 / 5,54
4. SS – 60 t/ha	0,22 / 0,16	0,27 / 0,13	0,28 / 0,33	0,82 / 0,61	5,82 / 5,87
5. SS – 80 t/ha	0,24 / 0,17	0,27 / 0,15	0,28 / 0,32	0,87 / 0,63	6,28 / 6,29
6. Compost (SS + sawdust (3:1)) – 60 t/ha	0,26 / 0,16	0,25 / 0,14	0,29 / 0,34	0,79 / 0,54	5,49 / 5,50
7. Compost (SS + straw (3:1)) – 20 t/ha	0,26 / 0,15	0,25 / 0,12	0,28 / 0,35	0,72 / 0,52	5,19 / 5,21
8. Compost (SS + straw (3:1)) – 40 t/ha	0,21 / 0,15	0,28 / 0,12	0,26 / 0,33	0,76 / 0,53	5,45 / 5,46
9. Compost (SS + straw (3:1)) – 60 t/ha	0,22 / 0,15	0,30 / 0,14	0,25 / 0,34	0,80 / 0,54	5,44 / 5,49
10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha.	0,21 / 0,15	0,23 / 0,13	0,28 / 0,33	0,79 / 0,54	5,32 / 5,36

Note. Above the line - in the soil layer 0 – 20 cm; under the line - in a layer of 20 – 40 cm.

The dependence of energy reserves in the soil on the ratio of humic and fulvic acids in the 0 – 20 cm soil layer (Fig. 5) can be described by the linear regression equation:

$$y = 4.1703\ x + 2.0447 \tag{3}$$

where y is the energy reserve in humus, GJ/ha;

x is the ratio of Sha : Sfa.

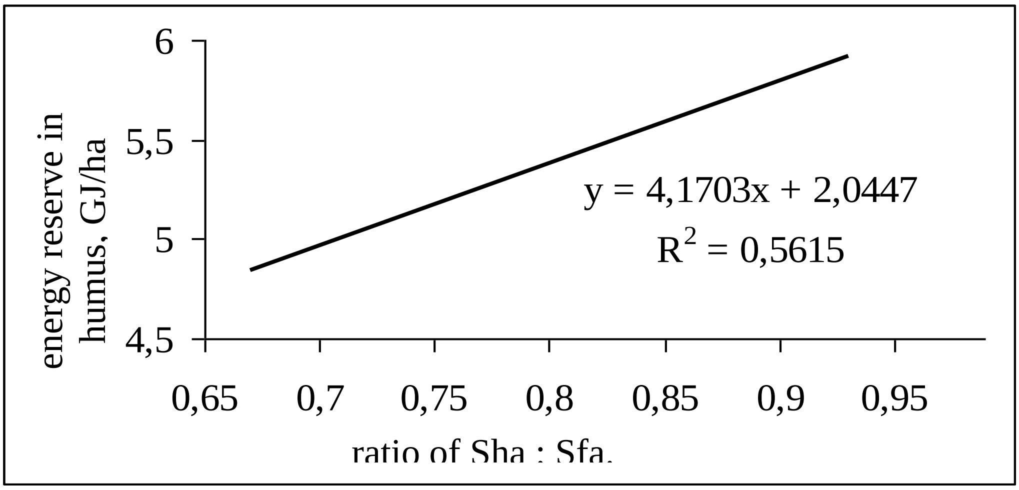

Figure 5. Dependence of the content of energy reserves in humus in the 0 – 20 cm layer of sod-podzolic soil on the ratio of Sha : Sfa.

The multiple coefficient of determination (R^2 = 0.56) reflects the significant dependence of the amount of accumulated energy in humus on the content of humic acids.

The dependence of energy reserves in the soil on the ratio of humic and fulvic acids in the 20 – 40 cm layer (Fig. 6) can be described by the following linear regression equation:

$$y = 13{,}223x + 0{,}1967, \tag{4}$$

where y is the energy reserve in humus, GJ/ha;

x is the ratio of Sha : Sfa.

In the lower layer (20 – 40 cm) of the soil horizon, the dependence of the amount of energy reserves in humus on the humic:fulvic acid ratio was much closer and the multiple coefficient of determination was R^2 = 0.91.

These researches make it possible not only to estimate the reserves of energy accumulated in the soil, but also reflect the ways of approaching the energy balance of the energy willow agrocenosis, since the nature and intensity of the main processes are related to the reserves of assimilated solar energy, which is accumulated in the humus of the soil and serves as the main source for various biotic and mineral transformations [328 – 331, 365 – 368].

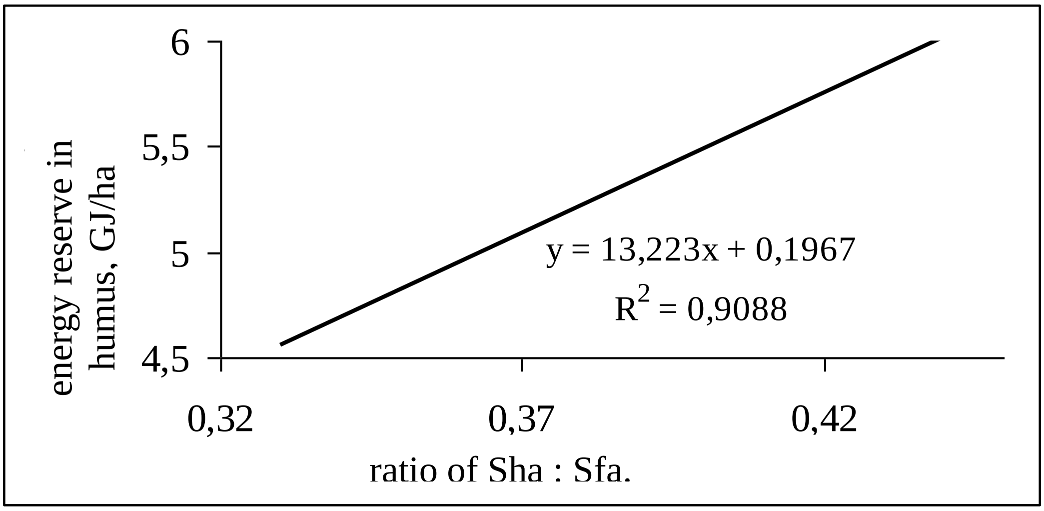

Figure 6. Dependence of the content of energy reserves in humus in a layer of 20-40 cm of sod-podzolic soil on the ratio of Sgk: Sfk.

Under the conditions of the experiment, the introduction of SS and composts based on it provide a qualitative improvement in the energy intensity of humus of sod-podzolic soil in the variants with the introduction of SS 80 t/ha and compost based on it with sawdust (3:1) at a dose of 60 t/ha. In the HE and E horizons, the energy content of humus is 6.3 and 5.5 GJ/ha, respectively, that is, by 0.9 – 1.7 GJ/ha, the similar indicators of the control variant prevailed [333, 361 – 363].

According to the results of the study of the features of the accumulation and transformation of humus compounds in the soil under the influence of the introduction of SS and composts based on it, the following basic patterns were established:

- with the introduction of SS, the content of total humus in the soil increases compared to the control without fertilizers. In particular, when it was applied at a dose of 40 t/ha, the humus content after the third year of vegetation of energy willow was 1.76% in the 0 – 20 cm layer and 0.40% in the 27 – 42 cm layer;

– with the introduction of 60 and 80 t/ha of SS, the humus content at a depth of 0-20 cm increases to 1.88 and 1.97% and decreases with depth to 0.43%. With the introduction of SS compost + sawdust (3:1) – 60 t/ha, the humus content is 1.70% in the upper (0 – 20 cm) layer. The application of mineral fertilizers even contributes to the reduction of the content of humus in the humus-eluvial horizon by 0.02% compared to the option without the application of fertilizers. In the eluvial and illuvial horizons, the humus content in these variants is 1.44 and 0.37%, respectively;

– the highest indicators of the content of active (labile) humus were observed in variants where the highest doses of organic fertilizers were applied.It is worth noting that in almost all variants of the experiment, the content of labile humus in the upper layer ranged from 0.61 to 0.64%;

- in contrast to the indicators of the content of labile humus, the indicators of passive (stable) humus increase with the application of SS. When it is applied in a dose of 40 t/ha, the content of passive humus is 1.07%. As the dose increases, the content of passive humus also increases to 1.1%;

- indicators of the fractional-group composition of humus indicate that without the application of fertilizers, the humus condition of sod-podzolic soil deteriorates, and the use of SS helps to increase the share of humic acids as the most valuable fraction of humus. The content of humic and fulvic acids in humus depends on the energy willow fertilization system. With the introduction of SS in a dose of 40 – 80 t/ha, the proportion of humic acids increases and the proportion of fulvic acids decreases. Mineral fertilizers partially stop the degradation processes of humus compounds, but worsen the quality of humus due to the increase in the proportion of fulvic acids in it, especially in the subsoil (20 – 40 cm) layer.

- the introduction of SS and composts based on them ensures an increase in the energy intensity indicators of humus of sod-podzolic soil. In the variants with introduction of SS at a dose of 80 t/ha and compost based on SS with sawdust (3:1) at a dose of 60 t/ha. Under such conditions, the energy intensity of humus is 6.3 and 5.5 GJ/ha, respectively, which is 1.7 – 0.9 GJ/ha higher than the similar indicators of the control option without fertilizers.

Multiple coefficient of determination (R^2= 0.73), coefficient of linear correlation (r=85) indicate a strong relationship between these indicators.

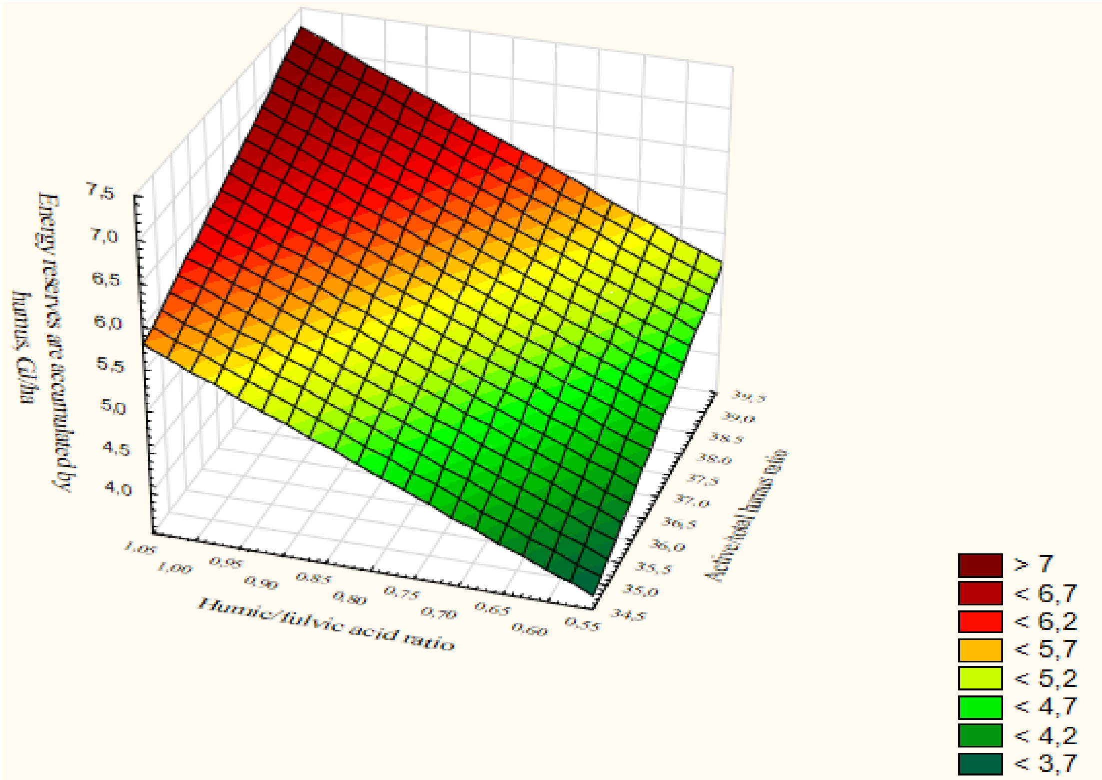

Figure 7. Dependence of the energy reserve value accumulated by humus. from the active/total humus ratio indicator and the content of the humic acid/fulvic acid ratio indicator

For this dependence, the multiple regression equation can look like this:

where *z* is the energy reserve value accumulated by humus.

$$z = -8.8914+0.2958*x+4.2626*y$$

x is an indicator of the active/total humus ratio

y is an indicator of the humic/fulvic acid ratio

Thus, the introduction of SS under the energy willow in fresh form and in the form of composts with various organic materials leads to significant changes in the humus state of Aluvisol, contributes to the growth of the share of passive humus and humic acids in humus, and leads to an increase in the energy content of humus.