DOI: 10.2478/ahr-2024-0003
Acta hort regiotec, 27, 2024(1): 15–22

Research Article

The Use of Products from Leonardite to Improve Soil Quality in Condition of Climate Change

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Article Details: Received: 2023-09-18 | Accepted: 2024-02-10 | Available online: 2024-05-31

The principle of sustainable fertilisation in modern agriculture, which ensures that the soil is maintained in a fertile state requires the search for alternatives to manure fertilisation for products based on humic substances to increase the organic matter content of soils.The advantage of leonardite over conventional natural and organic fertilisers is mainly due to its high content of organic matter and humic substances (humic and fulvic acids). Leonardite, due to the presence of humic acids in it, can be suitable for soil amendment and yield of barley. In the conducted studies, the yield increase after adding Rosahumus fertilizer to the soil at a rate of 6 kg.ha^{-1} + NPK (Nitrogen, Phosphorus, Potasssium) was found to be 11% compared to the control (NPK).There were no changes in the $C_{org.}$ content of the soil as a result of the application of Rosahumus fertilizer with NPK. The fertilizer only slightly modified the fractional composition of humus. In the future, we should expect an increase in the use of leonardite-derived humic substances in fertilizers and soil conditioners to stabilize soil organic matter.

Keywords: soil organic carbon, soil fertility, humic acids, fulvic acids, humins

1 Introduction

Climate change may exacerbate negative phenomena such as erosion, decline in soil organic matter, salinisation, loss of soil biodiversity, landslides, desertification and flooding (KLIMADA, 2019). A temperature increase of about 2–4 °C is expected in Poland, at the end of the 21st century. The predicted increase of air temperature and evaporation will affect soil water relations, which determine most soil processes (Łabędzki, 2009). The predicted intensification of soil degradation processes will lead to further losses of organic matter and a reduction in the functioning of the soil, thus reducing its fertility and productive capacity (Rogala, 2020). Under the influence of intense precipitation, soil aggregates will be destroyed (Rzekanowski, 2000). These changes will mainly increase surface runoff, reduce infiltration, permeability, and water retention capacity. The drying out of soils and the predicted reduction in the moisture content of the topsoil in summer may manifest itself in adverse changes in the physico-water properties. The consequences of this increase will be seasonal changes in the amount of precipitation and the intensity of extreme weather events, which will affect the quality of soils and the yield of crops (Łabędzki, 2009). The draft Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Conservation, 2021) indicates that EU member states will be obliged to develop ways of assessing soil health at different scales from regions to individual fields through the use of various indicators describing the chemical, physical, and biological properties of soils. The intensification of crop production, which has been progressing for several years now, requires the introduction of simplified rotations and very often the cultivation of mainly cereal crops in monoculture, which is important for humus quality, i.e. the predominance in the total organic carbon pool of a specific group of humic substances (Pikuła & Ciotucha, 2022). This is compounded by the adverse effects of climate change on soils and soil processes. There may therefore be adverse changes in soil structure due to drying and reduced humus content. Each soil has a specific type of humus, which differs not only in

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the quantitative but also in the qualitative composition of humic substances, as well as in the form of their binding to the mineral part of the soil . Researchers is constantly looking for new, environmentally and human-safe sources of organic matter to mitigate the decline in soil humus caused by climate change, as well as by growing crops in monoculture. Scientific experience confirms that humic substances positively affect soil fertility and plant growth, mainly due to their high cation exchange sorption, oxygen content and high water holding capacity (Akimbekov et al., 2020). The release of macro- and micronutrients into the soil from leonardite structures is slow, thus preventing their loss through leaching or evaporation, and the presence of humic acids also results in plant roots that are generally larger, more branched and denser, and have a larger surface area (Turgay et al., 2010).

Humic substances increase the water holding capacity of the soil, improve soil structure, and increase soil microbial activity, thereby improving nutrient uptake (Sharif, 2002). Humic acids derived from leonardites can be used as growth stimulants or applied topically in high doses as soil conditioners, which affect the soil by positively modifying its structure and increasing the activity of soil microbial populations (Pikuła, 2016). Notwithstanding some of the positive effects that can be attributed to an overall improvement in soil fertility following the introduction of leonardite, so others appear to be due to the effects of humic compounds on the metabolic pathways involved in plant development, stimulating growth in terms of length, dry or fresh matter content. Their main advantage is that they increase the water holding capacity of light soils, making the risk of drought lower (Qian et al., 2015). They increase nutrient availability (reduce leaching and retain nutrients in the root zone), stimulate root system development and the growth of beneficial microorganisms. In addition, humic substances binding with clay minerals, cations, polysaccharides with the participation of microorganisms give the soil a tubercular structure, creating good water, and air relations, and better soil permeability. In turn, by forming chelate complexes with micro and macronutrients, they make nutrients more easily available to plants. The low content of humic acids, especially in sandy soils, results in poor retention of water and minerals in the soil, which, migrating deep into the soil profile, are beyond the reach of crop roots (Spigarelli, 1992).

Currently, a very popular source of it, due to the lack of manure leonardites (Pikuła, 2022). Leonardites are the end result of a humification process of organic matter lasting several tens of millions of years. Leonardites is therefore a fossil that is an intermediate form between peat and lignite (Turgay et al., 2010). A soft and shiny mineraloid, black or brown in colour, which is one of the most valuable sources of organic matter, including humic compounds. Leonardite is named after Dr Arthur G. Leonard, who was the first to discover and begin researching deposits of this mineral. The term leonardite also refers to partially oxidised forms of low-grade coals, including sub-bituminous coals and coal shales. There are mainly three types of leonardite used in research. The first is a black, colloidal material that swells on contact with water, but retains its volume for some time. It is completely soluble in alkalis and forms a distinctly dark brown solution in them, from which, at low pH, a colloidal precipitate can be precipitated equivalent to naturally occurring humic acids in the soil. The second type is a mixture of type one leonardite and lignite, while the third type is mine leonardite, resembling a precipitated product of type one leonardite in the laboratory. A characteristic feature of leonardites is their high content of organic matter, including humic substances (humic acids), which allows them to be used as soil conditioners, or as ion exchange stabilisers or remediators of contaminated soil environments. The average content of humic acids in leonardites is estimated to be 60–70% and can reach up to 90% content in dry matter. The amount of humic acids obtained depends on the maturity of the coal and the nature of the coalification process involved in its formation. Humic substances originating from various organic matters can ameliorate soil properties, stimulate plant growth, and improve nutrient uptake. Due to the low calorific heating value, leonardite is rather unsuitable as fuel. However, it may serve as a potential source of humic substances (Akimbekov et al., 2020; Akinremi et al., 2000). As described in many literature works, leonardite represents sediments enriched with inhumic acids, which occur at shallow depths (Akinremi et al., 2000). The aim of this sudy was an assesnemnt of the effectivness of the applied products from lepnardite for improving the performances of selected soil paramtetres and yields of plants.

2 Material and methods

The experiment was establised by using soil and plant materials from field experiments in Grabow (Lat: 51° 21′ 08″ N; Long: 21° 40′ 08″ E), belonging to the Institute of Soil Science and Plant Cultivation in Puławy, Poland. The soil was classified as an Albic Luvisol (IUSS WRB, 2022; World reference base for soil resources (2022) and has the loamy sand texture (70% sand, 25% silt, 5% clay). The climate at the site is temperate with a the mean annual rainfall on the level of 560 mm and the mean annual air temperature 7.8 °C (based on 36-year climatic data collected from 1980 to 2016). This climate is considered as Dfb i.e. warm humid continental climate, according to the Köppen-Geiger climate classification. Rosahumus (Agrosimex) – formulation produced on a leonardite basis were used as sources of organic matter. Rosahumus is a completely water-soluble organic-mineral fertiliser containing humic acids, potassium, and iron. Chemical composition: 56% organic matter, including: 85% humic acids 12% water-soluble potassium oxide (K_2O) 0.6% water-soluble iron (Fe). The humic preparation acts as a soil conditioner and biostimulator for plant development. It is recommended for soils with a low humus content, where no manure is used and for farms using simplified crop rotation with a predominance of cereal crops.

The experiment with the Rosahumus preparation was established on lessive soil developed on light clay belonging to the very good rye complex. The soil was characterised by an alkaline reaction, high abundance of phosphorus, very low abundance of magnesium, and medium abundance of available potassium. The $C_{org.}$ content was 0.73%. The basic soil characteristics are summarised in Table 1.

The experimental fields were drained, with good drainage condition and the soil was characterised by good water-air relations. The test crop was spring barley, variety Kucyk. The area of the harvest plots was 15.0 m^2 (10.0 m long and 1.5 m wide). The experiments investigated the effect of Rosahumus on barley grain yield and the properties of the soil were selected-pH (pH in the suspension KCl ($mol.dm^{-3}$) PN-ISO 10390:199 – the content of SOC by the Turin method (PB 021-issue IV.28.08.2020), and detailed soil organic quality tests like the fractionation of organic matter by the Schnitzer method were also performed. Based on the obtained results, the percentage share of individual fractions in the total pool of organic carbon was calculated. The carbon of the humin fraction calculated from the difference between organic carbon and the sum of marked factions. The content of organic carbon of separated fractions was calculated as follow:

CD-carbon in extracts after soil decalcification with 0.025 M HCl (extraction for 24 h at room temperature)
HA + FA-carbon of the sum of humic and fulvic acids in extracts obtained with 0.5 M

NaOH (extraction for 24 hours at room temperature)

FA-carbon of fulvic acids in solutions after precipitation of humic acids with 6 M HCl

to pH = 2) (extraction for 24 hours at room temperature)

HA - carbon of humic acids calculated from the difference:

$$HA = HA + FA - FA$$

$$H = 100 - (HA + FA + CD)$$

Dehydrogenase activity was estimated using TTC (2,3,5-triphenyltetrazolium chloride) as the substrate and, in the case of phosphatases (acid and alkaline), p-nitrophenyl phosphate (PNP) was used as the substrate. Rosahumus fertiliser was applied at topdressing before sowing barley in the form of a spray at the following rates against the control treatment, according to the scheme:

Rosahumus:

1. Control (full NPK (Nitrogen, Phosphorus, Potasssium) dose: N-15 $kg.ha^{-1}$, P_2O_5 – 50 $kg.ha^{-1}$, K_2O – 75 $kg.ha^{-1}$).
2. Rosahumus 6 $kg.ha^{-1}$ + full NPK dose.
3. Rosahumus 6 $kg.ha^{-1}$ + half dose of NPK.
4. Rosahumus 3 $kg.ha^{-1}$ + Delsol 1 $l.ha^{-1}$ + full NPK dose.

Preparation containing humic compounds was applied in doses according to the manufacturer's recommendations. DELSOL microbial fertiliser containing 3% total nitrogen including amide nitrogen 2.4%, organic nitrogen 0.6% and carbon „co-formulator" to stimulate the growth of beneficial soil bacteria.

2.1 The course of the weather conditions

The long-lasting snow cover meant that spring plant vegetation and agronomic treatments did not begin until the first decade of April. May and June saw heavy, frequent rains. Rainfall totals were almost double the multi-year averages. These conditions resulted in the formation of local water ponds, which translated into spring barley yields. In the following months (July, August), rainfall totals were several times lower than multi-year averages, while temperatures remained high. The high temperatures caused localised soil crusting, resulting in stunting or partial crop failure. The precipitation distribution and temperature totals for the 2012/2013 growing season are shown in Figs 1 and 2.

Table 1 Soil characteristics of the experiment

Plant	Type and type of soil	Agricultural suitability complex	mg in 100 g of soil			pH_{KCl}	$C_{org.}$ (%)
			P_2O_5	K_2O	Mg		
Spring barley	loamy soil formed from light loamy sand	very good rye: R-IIIa	16,3	15,4	2,7	7,29	0,73

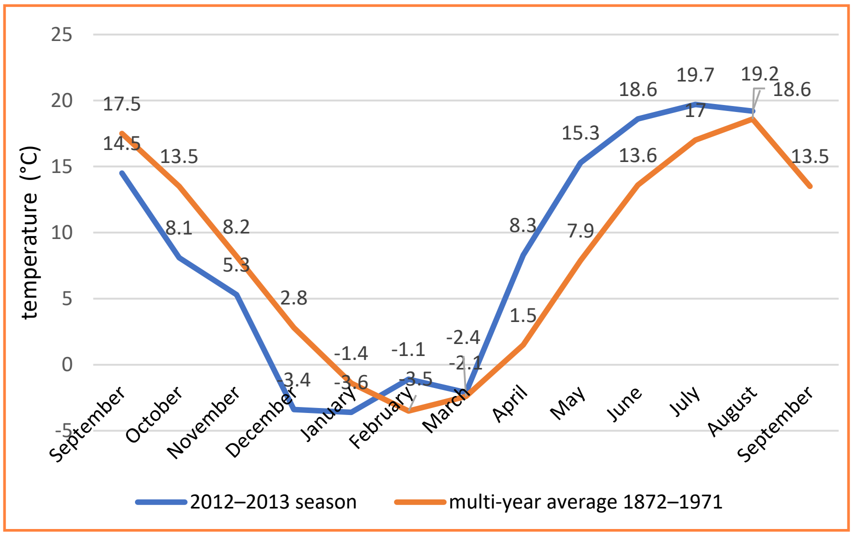

Figure 1 Temperature distribution in the 2012–2013 growing season compared to the multi-year period

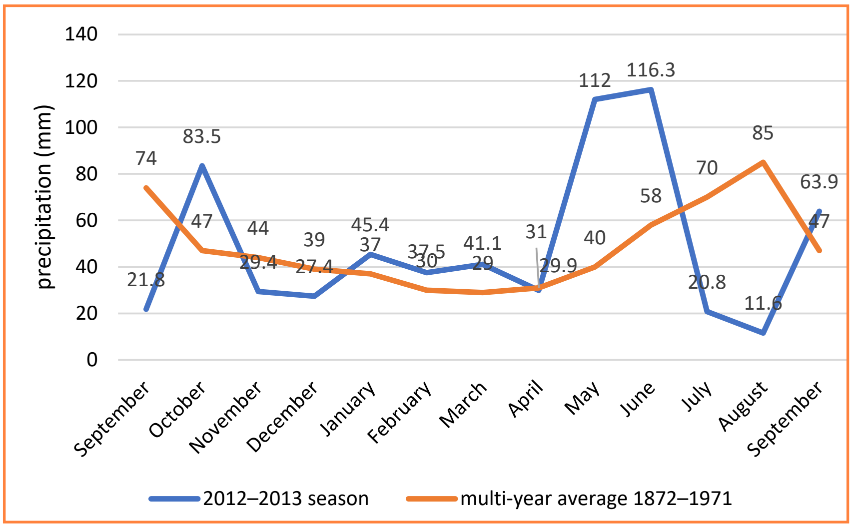

Figure 2 Distribution of precipitation during the 2012–2013 growing season compared to the multi-year period

3 Results and discussion

3.1 Effect of humic substances from leonardites on root system development

In scientific experiments, the effectiveness of humic substances on soil and plants is generally assessed by adding humic substances extracted from leonardite to nutrient solutions or tested in field trials by spraying plants or soil. Scientific research and agricultural practice confirm that humic substances, which, in addition to humic acids, fulvic acids and humin, also contain significant amounts of nutrients, i.e. potassium, magnesium, and nitrogen, have a beneficial effect on plant development and yield, and their use over a longer period of time also improves some soil properties (Akimbekov et al., 2020; Spigarelli, 1992). It is also very common to see an increase in root mass, particularly trichome roots extremely important in nutrient and water uptake. Mostly, the roots of crops in soils to which humic substances are added are twice as long and retain their vigour longer, which makes the plant able to take up water from deeper soil layers and better utilise nutrients from the soil (Akimbekov et al., 2020). The study conducted also confirmed such a trend. The root system was sampled using the open pit method at the 6–8 leaf and milk maturity stage and after harvest of spring barley. Noticeable differences in the

Figure 3 Root system at the 6–8 leaf stage of spring barley after application of Rosahumus in different combinations
Site 1 (100% NPK), Site 2 (Rosahumus 6 kg.ha^{-1} + 100% NPK), Site 3 (Rosahumus 6 kg.ha^{-1} + 50% NPK), Site 4 (Rosahumus 3 kg.ha^{-1} + Delsol 1 l.ha^{-1} + 100% NPK)

Rosahumus object 1 | Rosahumus object 2 | Rosahumus object 3 | Rosahumus object 4

Figure 4 Root system at milk maturity of spring barley after application of Rosahumus in different combinations
Site 1 (100% NPK), Site 2 (Rosahumus 6 kg.ha^{-1} + 100% NPK), Site 3 (Rosahumus 6 kg.ha^{-1} + 50% NPK), Site 4 (Rosahumus 3 kg.ha^{-1} + Delsol 1 l.ha^{-1} + 100% NPK)

structure of the barley root system occurred at 8 weeks after sowing. The addition of humic substances from leonardite tended to increase the plant height, as well as the number of roots (Fig. 3).

At the 6–8 leaf stage, Rosahumus applied together with NPK fertilisation caused the development of spring barley lateral roots (Fig. 3). The highest density of lateral roots was obtained on the treatment where Roshumus was applied together with Delsol (Treatment – Rosahumus 3 kg.ha^{-1} + Delsol 1 l.ha^{-1} + full dose of NPK) compared to the control (NPK). Such a relationship was also obtained at the milk maturity stage of spring barley.

At the stage of milk maturity of spring barley, the root system on the treatments where Rosahumus was applied without the addition of Delsol fertiliser was similar to that on the control treatment (NPK) (Fig. 4).

3.2 Effect of humic substances from leonardites on yields

The use of humic-based preparations for plant dressing or spraying also leads to increased yields and increased plant resistance to adverse soil and climatic conditions and diseases. The more abnormal the conditions, the greater the effect of using humic compounds (Pikuła, 2016). Such a trend occurred in our study. The application of Rosahumus fertiliser together with NPK significantly affected spring barley grain yields. Under the effect of a dose of 6 kg.ha^{-1} of this fertiliser and a full dose of NPK, an 11% increase in spring barley grain yield was obtained compared with the control (NPK) (Fig. 5). There was also a 10% higher spring barley yield compared to the control (NPK) treatment on the treatment fertilised with Rosahumus together with Delsol and NPK. Reducing the NPK fertilisation rate by half resulted in lower barley grain yields.

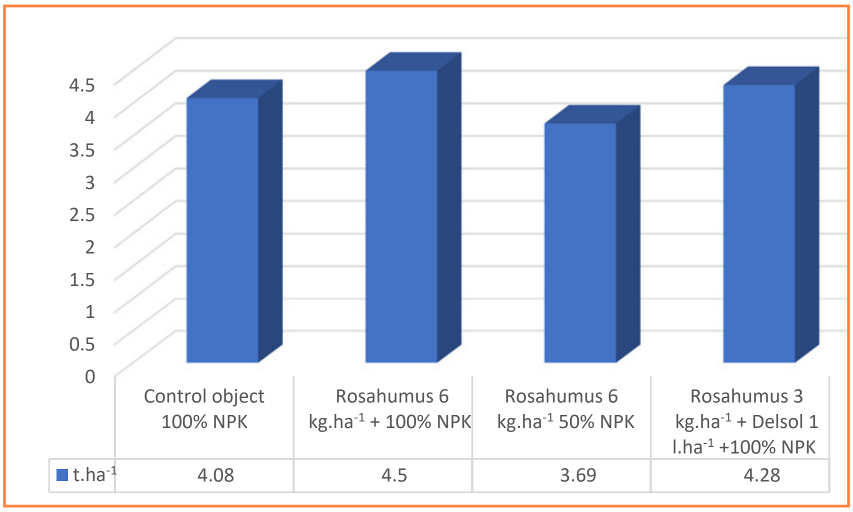

Figure 5 Spring barley yields influenced by the application of Rosahumus fertiliser in different combinations

The beneficial effects of humic substances on the development of the plant root system are of great importance in field cultivation, especially of spring crops (Kocoń, 2013). Spring plants are exposed to periodic droughts, which are important in reducing the yield of these plants as a result. Research confirms that in soils with applied humic acid preparations, spring plants draw more water from the deeper soil layer, which makes them more resistant to periodic droughts and the cells retain their turgor longer (Pikuła, 2016). This trait is particularly desirable in our climate, where periodic water shortages are relatively common, and there is a predominance of light soils and therefore more prone to water loss compared to heavier soils with a larger sorption complex (Pikuła & Ciotucha, 2022).

Preparations containing leonardite-derived humic acids applied as a foliar spray can also stimulate the growth of crop stems (Rutkowska, 2016).

Table 2 Chemical properties of the soil (0–30 cm) after harvesting spring barley

Treatment	pH (KCl)	(%)	
		$C_{org.}$	total N
Rosahumus control 100% NPK	6.7a	0.73a	0.058a
Rosahumus 6 kg.ha^{-1} + 100% NPK	6.8a	0.72a	0.059a
Rosahumus 6 kg.ha^{-1} 50% NPK	7.1b	0.81b	0.069b
Rosahumus 3 kg.ha^{-1} + Delsol 1 l.ha^{-1} + NPK	7.0b	0.72a	0.058a

Humic acids have direct and indirect effects on plant growth. A close relationship between the content of humic substances in the soil and plant yield has been proven (Ulukan, 2008). Maize, wheat or barley, on the other hand, under the influence of these substances yield from 25 to even 50% higher compared to the control treatments with standard NPK mineral fertilisation.

3.3 *Effect of humic substances from leonardites on soil properties*

The soil in the control treatments (full NPK dose) without Rosahumus fertiliser was characterised by a neutral reaction, high abundance of available phosphorus, medium abundance of potassium and low abundance of available magnesium. The $C_{org.}$ content of the soil was 0.73%. The soil on the control treatments with NPK without Delsol fertiliser showed a neutral reaction, high abundance in available phosphorus, high in potassium and low in available magnesium. The $C_{org.}$ content of the soil was 0.72% (Table 2). After the application of Delsol + NPK fertiliser, there was a slight increase in the abundance of available phosphorus and magnesium in the soil compared to the control (NPK). This effect was not obtained when Rosahumus fertiliser was added to the soil. The application of Delsol + NPK, and Rosahumus + NPK fertilisers in different combinations did not result in a significant increase in soil C_{org} and total nitrogen content compared to the control (NPK) treatment.

The application of Rosahumus fertilisers in different combinations slightly modified the fractional composition of humus (Fig. 2). After the end of the growing season in 2013, the % humin fraction increased slightly, compared to 2012, but also on the control sites.

The % fraction of fulvic acids decreased slightly in the C_{org} pool. No significant differences were found between the sites in the % fraction of fulvic, humic, and humic acids after application of Rosahumus fertiliser together with NPK (Fig. 6). Humic acid preparations applied at low doses show a stimulating effect on plants, while their effectiveness in improving soil fertility is evident when high doses of fertiliser are applied (Rutkowska, 2016).

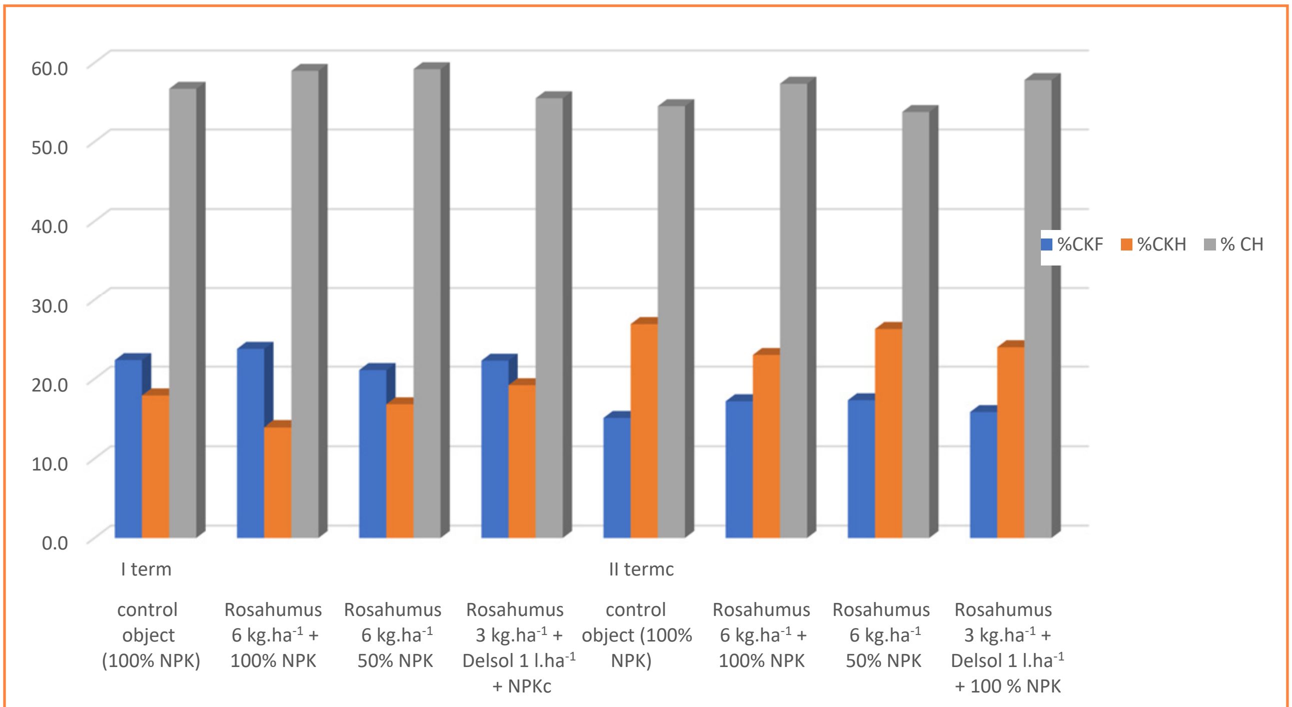

Figure 6 Humus fractions (%) after application of Rosahumus fertilizer in different combinations
1st term – July, 2nd term – August

Table 3 Microbiological properties of soil

Treatment	Acid phosphatase activity		Alkaline phosphatase activity		Dehydrogenase activity		Total bacterial count (cfu) in 1 g p.s.m. × 10^7		Fungal abundance (cfu) in 1 g p.s.m. × 10^3	
	I term	II term	I term	II term	I term	II term	I term	II term	I term	II term
Rosahumus – 100% NPK control	32.2	21.7	28.3	26.2	18.6	20.8	231	645	58	58
Rosahumus 6 kg.ha^{-1} + 100% NPK	34.0	19.5	28.7	27.0	21.1	35.2	63	494	76	55
Rosahumus 6 kg.ha^{-1} + 50% NPK	28.1	18.1	36.3	36.4	25.8	27.9	174	80	56	69
Rosahumus 3 kg.ha^{-1} + Delsol 1 l.ha^{-1} +NPK	39.1	20.4	34.4	33.5	38.9	37.8	294	191	91	50

1st term – July, 2nd term – August

As a result of the increase in soil moisture and temperature, the conditions for the development of microorganisms and biological life in the soil improved after the application of Rosahumus. Microbiological tests were carried out in soil samples. The total abundance of bacteria and fungi was determined, as well as the activity of the enzyme dehydrogenase indicating the activity of soil microorganisms. The activity of acid phosphatase and alkaline phosphatase – enzymes involved in phosphorus metabolism in soil – was also determined. The microbiological properties of the soil are shown in Table 3. No statistically significant differences were found in the abundance of bacteria and fungi after application of the Rosahumus preparation. Only in July did this formulation in combination with Delsol and NPK significantly increase the abundance of microorganisms. The activity of enzymes from the dehydrogenase group was lowest in the control treatment, i.e. in soil without the addition of the tested preparations. The effect of the preparations on acid and alkaline phosphatase activity was more variable. In August, acid phosphatase activity was highest in the soil of the control treatment, but the values found were not significantly different. In July, a significantly higher activity of this enzyme was found in the soil of treatment 4. In both dates, alkaline phosphatase activity had significantly higher values in treatments fertilised with Rosahumus +1/2 NPK and Rosahumus + Delesol + NPK than in the control treatment or in the treatment with Rosahumus + NPK. These results confirm that the introduction of leonardite-based humic substances into the soil has a beneficial effect on the composition and number of microorganisms and enzymatic activity in the soil (Dong et al., 2009; Puglisi et al., 2009).

Usually, a more beneficial effect of humic substances on plants is seen in soils with regulated pH and calcium-rich soils, and when applied as a spray than when applied topically (Rutkowska, 2016). In contrast, when applied on acidified soils, they show a protective effect. Agricultural research conducted at the Institute of Soil Science and Plant Cultivation on the effectiveness of humic preparations on crop yields and soil fertility only confirms the effectiveness of these preparations on soils with regulated pH, where optimal NPK fertilisation is applied (Pikuła, 2016). Depending on the formulation, the soil fertility of this nutrient, which is present in a higher concentration in the formulation, may periodically improve (Ulukan, 2008).

4 Conclusions

Leonardite, due to the presence of humic acids, can be suitable for soil amendment and yield improvment of barley production. In the experiments conducted, an 11% yield increase was observed after adding Rosahumus fertiliser to the soil at a dose of 6 kg.ha^{-1} + NPK compared to the control (NPK). Reducing the NPK dose by half resulted in a reduction in spring barley yield and was not mitigated by the addition of Rosahumus fertiliser. Rosahumus fertiliser stimulated the development of spring barley root mass at the 6–8 leaf stage. The analysed microbiological and chemical properties of the soil were characterised by high variability. No significant effect of Rosahumus fertiliser applied with NPK on soil microbiological and chemical properties was shown. No changes in soil $C_{org.}$ content were shown as a result of the application of Rosahumus fertiliser with NPK. The fertiliser only slightly modified the fractional composition of humus. In the future, an increase in the use of leonardite-derived humic substances in fertilisation and soil conditioners is to be expected in order to stabilise soil organic matter.

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