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Qualitative composition of humus and physical and chemical properties of typical chernozem depending on the fertiliser system

Abstract. The soil-forming process is closely related to the accumulation and circulation of organic substances, which are a source of nutrients for plants released during the mineralisation of humus, so research on determining the qualitative composition of humus is relevant. In this regard, the purpose of this paper is to determine humic and fulvic acids in typical chernozem, depending on the fertiliser system. The leading approaches to solving this problem are conducting field and laboratory studies to determine the quality indicators of humus and dispersion methods to establish the

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accuracy and reliability of experimental data. Based on the conducted studies, it was observed that the application of an organo-mineral fertiliser system leads to an increase in the content of humic acids, while the insoluble residue shows an increase in carbon content. The utilisation of organo-mineral fertilisers resulted in a reduction in the excessive accumulation of non-humified organic substances. Additionally, the soils in these areas exhibited a higher level of organic substance humification. The combination of organic matter at a rate of 11.5 tonnes per hectare (8 tonnes of manure and 3.5 tonnes of by-products) and mineral fertilizer $N_{27}P_{38}K_{45}$ in a crop rotation resulted in an increasing trend of the buffering capacity of typical chernozem soil. In this scenario, there was an increase in absorption capacity at the end of the second rotation for grain-legume crop rotation by 6.05 mg/equiv per 100 g, specialised grain-legume rotation by 3.9 mg/equiv per 100 g, and legume rotation by 3.06 mg/equiv per 100 g of soil compared to the beginning of the first rotation. The use of organo-mineral fertilisers increases the third fraction of fulvic acids in specialised grain-legume rotation, which affects the ratio of humic acids to fulvic acids in favour of the humic type of humus formation. The ratio of humic acids to fulvic acids in the grain-planting crop rotation in the organo-mineral system was 2.84 at the end of the second rotation, and 2.24 at the beginning of the first rotation. The research materials are of practical importance for farmers when analysing the fractional-group composition of typical chernozem humus

Keywords: humic acids; fulvic acids; humic content; fractional composition; fertiliser system

INTRODUCTION

The organic matter of the soil is a key factor that reflects the level of potential soil fertility, and is of great importance in controlling biological and physico-chemical processes in the soil, and in providing plants with the necessary nutrients (Lin *et al.*, 2019; Tsyuk *et al.*, 2022). In chernozem soils, organic matter is mainly represented by humus, and its content and reserves depend on the plant cultivation technologies used. Changes in the content and reserves of humus will be determined by the relationship between the processes of humification (formation of humus) and mineralisation (decomposition of organic matter into mineral components) in the context of applied technologies. The amount of organic fertilisers and plant residues that enter the soil has the greatest impact on this relationship (Tsyuk *et al.*, 2018). One of the important factors for promoting humification processes is the application of mineral fertilisers at optimal

standards, in particular nitrogen. The optimal ratio of carbon to nitrogen is 25-30:1. Humus mineralisation occurs during the cultivation of agricultural crops, and the intensity of this process depends on the biological characteristics of plants. The main strategies for preserving and restoring organic matter, as well as soil fertility, are the biologisation of fertiliser systems and the use of biological methods (Volkohon *et al.*, 2019; Tanchyk *et al.*, 2021).

Given the versatility of generalisations, the issues related to studies of the influence of fertiliser systems in various crop rotations on the quality of humus and the physical and chemical properties of typical chernozem are quite relevant. The group composition of humus is a consequence of direct processes of transformation of organic mass, which is related to the fertiliser system of agricultural crops (Tkachenko & Hryhora, 2013; Tsvei *et al.*, 2016).

As noted by E.S. Hasanova *et al.* (2010), humic acids exhibit the maximum ability for ion exchange interaction, which is due to their high molecular weight and more complex chemical structure compared to fulvic acids. Therewith, the authors indicate that exclusively mineral fertilisation of agricultural crops leads to the intensive destruction of all high-molecular fractions of humic acids.

Humic acids, which are formed during the synthesis of humus in the soil, are considered essential components of the soil according to numerous studies. They have a special nature and characteristics that distinguish them from other soil components (Tsentilo, 2019; Marenych *et al.*, 2020).

Y. Kravchenko *et al.* (2022) concluded that long-term use of organic fertilisers leads to an increase in humic acids in the composition of humus, which leads to a broader HA: FA ratio. Formation of organic compounds mainly of the fulvic acid type under the influence of mineral fertilisers (Lin *et al.*, 2019; Demydenko *et al.*, 2021). This claim is supported in other studies (Hospodarenko *et al.*, 2022).

The author states that introducing solely mineral fertilisers increases the fulvic acid level of the humus. Moreover, the systematic application of organic-mineral and organic fertilisation systems leads to a certain increase in the humification of humus.

Long-term application of manure and mineral fertilisers on chernozem soils provided an increase in the content of humic acids and a decrease in the amount of fulvic acids and non-hydrolysed residue compared to the option without fertilisers (Degtyarev *et al.*, 2020; Degtyarev & Chekar, 2020; Lin *et al.*, 2021).

The purpose of the study is to investigate changes in the quality indicators of humus in typical deep chernozem depending on the fertiliser system in short-rotation crop rotations.

MATERIALS AND METHODS

The research on qualitative changes in humus was conducted as part of a long-term study at Bila Tserkva National Agrarian University from 2012 to 2021.

The experimental soil area is a typical deep low-humus medium-loamy chernozem with a humus content in the upper soil layer (0-30 cm) in accordance with DSTU 4289:2004 (2005) – Soil quality. Methods for determining organic matter – in the range of 3.7-3.94%. The level of hydrolysed nitrogen is 110 mg/kg of soil according to DSTU 7863:2015 (2016) – Soil quality. Determination of easily hydrolysed nitrogen by the Cornfield method. According to DSTU 4114-2002 (2003) Soils, the content of available phosphorus and exchangeable potassium is 120 mg/kg and 110 mg/kg of soil, respectively. Available phosphorus and potassium compounds were determined using the modified Machigin method. The water-physical properties of the soil of the experimental site are favourable. The density of the treated soil layer varies between 1.16-1.25 g cm³, and the total crevice is 52-55%. The area of the sown plot is 171 m², and the accounting plot is 112 m², with repetition 3 times. Agricultural techniques for growing crops are generally accepted for this zone.

The short-rotation crop rotations included the following crops: for the grain-legume rotation, grains accounted for 60% and legume rotation for 40% (soybeans – winter wheat – sunflower – barley – corn for grain); for the specialised grain-legume rotation, grains accounted for 40%, legumes for 40%, and cereals for 20% (buckwheat – winter wheat – corn for grain – sunflower – barley – sunflower); for the legume rotation, grains and grain legumes accounted for 40% and legumes for 60% (peas – winter wheat – sunflower – corn for grain – sunflower).

Gradations of fertiliser systems. Zero level – no fertilisers. Organo-mineral – to restore soil

fertility, priority is given to the use of organic fertilisers, such as applying 8 tonnes of manure per hectare of crop rotation area and 3.5 tonnes of biomass from cover crops, non-productive crop residues. Additionally, 110 kg of mineral fertilisers ($N_{27}P_{38}K_{45}$) are applied. The fertilisers applied included semi-rotted manure from large cattle on straw bedding, ammonium nitrate, regular granulated superphosphate, and potassium salt.

In all variants, the remaining wheat straw was crushed after harvesting and driven into the soil with a disc harrow. After harvesting wheat, the soil was prepared for sowing white mustard as a cover crop. In late September and early October, post-harvest mustard crops in all variants were planted in the soil.

Soil samples were collected from a depth of 0-25 cm in three replications. To form a mixed soil sample, 5 individual samples were taken using a grid sampling method. Soil sampling and preparation for analysis were conducted in accordance with the requirements of DSTU 4287:2007 (2005). The analysis of soil samples was performed in accordance with the current regulatory and methodological documents: pretreatment of the sample according to DSTU ISO 11464:2007 (2012); determination of the total carbon content by the Tyurin method according to DSTU 4289:2004 (2005); establishment of the group and fractional composition of humus by the Tyurin method modified by Ponomarev and Plotnikov according to DSTU 7828:2015 (2015).

A notable difference between the variants was determined by the LSD criterion at a 95% probability level by the method of variance and correlation analysis according to B.O. Dospekhov (1985) using the Excel software package.

RESULTS AND DISCUSSION

Over the past twenty years, the application of mineral fertilisers in crop rotations on typical

chernozems has notably altered the fractional composition of humus (Polevoy, 2007). The amount of humic acids (fraction 1) decreased by 0.03% in the variant without fertilisers in the grain-legume and specialised grain-legume crop rotations. A similar pattern occurred in the organo-mineral fertiliser system, and a decrease in the content of humic acids was observed (Table 1). The effectiveness of fertilisers influences the activation of humic acids, which are accompanied by the decomposition of high-molecular-weight fractions into low-molecular-weight ones. This can be explained by the fact that organic and mineral fertilizers contain oxidisers that contribute to the breakdown and peptisation of humic acids.

There is also a decrease in the second fraction of humic acids in the presence of both the organic-mineral fertiliser system and the absence of fertilisers. This decrease is influenced by the inclusion of sunflower in the crop rotation as well as the presence of leguminous crops.

A considerable decrease occurred in the grain crop rotation, where the proportion of humic acids of the second fraction decreased by 23.2%, which amounted to -0.86% for the organo-mineral fertilisation system.

Notably, regarding the content of humic acids (fraction 3), which are associated with stable semioxidants and clay minerals, an increase in their content occurs in the grain-legume crop rotation until the beginning of the first rotation, in areas without the application of fertilisers and in the organo-mineral fertilisation system, while in the legume rotation, there was a decrease. In the grain-legume crop rotation, the application of mineral and organic fertilisers resulted in a 30% increase in their quantity (in relative terms), while in the specialised grain-legume rotation, it only stabilised and increased by 11%. In the legume rotation, it increased to 23% (Table 1).

Table 1. The group and fractional composition of typical chernozem humus, %

Soil fertilisation system	C _{general} , %	Humic acids, %			HA, %	Fulvic acids, %			FA, %	HA: FA	Insoluble residue
		1	2	3		1	2	3			
Grain-legume crop rotation											
WF	2.51	0.06	0.92	0.22	1.20	0.10	0.15	0.17	0.42	2.85	0.89
	2.49	0.03	0.89	0.31	1.23	0.13	0.09	0.20	0.42	2.92	0.84
OM	2.56	0.09	0.83	0.20	1.12	0.10	0.20	0.21	0.50	2.24	0.94
	2.55	0.04	0.81	0.26	1.11	0.10	0.10	0.19	0.39	2.84	1.05
Specialised grain-legume rotation											
WF	2.42	0.06	0.98	0.19	1.23	0.11	0.34	0.14	0.59	2.08	0.60
	2.20	0.03	0.78	0.24	1.05	0.10	0.18	0.20	0.48	2.18	0.67
OM	2.46	0.09	0.99	0.18	1.25	0.11	0.29	0.20	0.60	2.10	0.61
	2.59	0.03	0.76	0.20	0.99	0.07	0.09	0.25	0.41	2.41	1.19
Legume rotation											
WF	2.41	0.05	1.05	0.13	1.23	0.14	0.44	0.16	0.74	1.66	0.44
	2.41	0.03	0.82	0.26	1.11	0.12	0.22	0.26	0.60	1.85	0.70
OM	2.54	0.05	0.93	0.16	1.14	0.13	0.45	0.20	0.78	1.46	0.62
	2.53	0.03	0.83	0.23	1.09	0.15	0.06	0.22	0.43	2.53	1.01

Note: WF – without fertilisers; OM – organo-mineral fertiliser system; numerator – beginning of the first rotation in 2012; denominator – end of the second rotation in 2021

Source: developed based on the conducted research

Under the influence of crop rotations, the fractions of fulvic acids also change. The amount of fraction 1 fulvic acids, associated with fraction 1 humic acids, decreased by 0.04% during grain-row crop rotation without fertilisers compared to row crop rotation. The use of mineral and organic fertilisers increased the amount of fulvic acids 1 during legume rotation by 0.08-0.12% compared to fraction 1 of humic acids. Fulvic acids of fraction 2, which are bound to fraction 2 of humic acids, decreased in all crop rotations both with the use of fertilisers and without them. The fraction of 3 fulvic acids, which is associated with the fraction of 3 humic acids, not only stabilised, their number increased by 0.03% compared to the beginning of the rotation.

A potential source of humus replenishment is the non-hydrolysed residue, which grew the most in grain-legume crop rotation by 0.11%. At

the end of the second rotation, the non-hydrolysed balance increased by 25.0% compared to the beginning of the first rotation. The humus content of typical chernozem in crop rotations increases considerably due to an increase in the amount of non-hydrolysed residue. The ratio of humic acids to fulvic acids in grain-planting crop rotation in the organo-mineral fertiliser system increased by 26.7% during grain-legume crop rotation compared to the beginning of the first rotation. In the specialised grain-legume rotation and the legume rotation, the ratio of humic acids increased by 10.5% and 36.7% respectively compared to the variant without fertilisers, corresponding to the humate type of humus formation in all crop rotations.

The content of humic acids of the second and first fractions decreased, while the third fraction increased. The content of fulvic acids

decreased, and the ratio between humic and fulvic acids increased, indicating a humate type of humus formation in the deep typical chernozem soil with low organic matter content.

Studies have shown that under the organo-mineral system, the soil buffering capacity increased in the grain crop rotation from 7.1 to 7.3, in the specialised grain crop rotation from 7.0 to 7.4, and in the legume rotation from 7.1 to 7.2 (Table 2, 3). It is explained by the fact that with the application of $N_{27}P_{38}K_{45}$ and manure, the content of Ca, Mg, and Na in the soil increased, and the effect of nitrogen and potash

fertilisers reduced due to the activity of these cations. Increased pH absorption capacity under the influence of fertilisers and crop rotations. Under organo-mineral fertilisation, there was an increase in cation exchange capacity in the grain crop rotation, with a value of 6.05 mg/eq per 100 g in the tillage layer. In the specialised grain crop rotation, the value was 3.9 mg/eq per 100 g, and in the legume, it was 3.06 mg/eq per 100 g of soil compared to the beginning of the first crop rotation. This can be explained by the replenishment of exchangeable cations in the soil-absorbing complex.

Table 2. Changes in the physical and chemical parameters of typical chernozems depending on fertiliser systems in the 0-25 soil layer at the beginning of crop rotation

Soil fertilisation system	Salt pH	S, mg/eq per 100 g of soil	Mg/eq per 100 g of soil	Ca, mg/eq per 100 g of soil
Grain-legume crop rotation				
Without fertilisers	7.0	44.19	1.61	16.70
Organo-mineral	7.1	44.1	1.90	17.7
Specialised grain-legume rotation				
Without fertilisers	7.0	44.56	1.55	16.90
Organo-mineral	7.0	44.30	1.73	17.4
Legume rotation				
Without fertilisers	7.0	43.80	1.55	16.60
Organo-mineral	7.1	45.35	1.75	17.30
LSD ₀₅	0.20	2.54	0.45	0.18

Source: developed based on the conducted research

The Ca content in areas without fertilisers decreased most for specialised grain-legume rotation by 1.80 mg/eq per 100 g of soil, legume – by 1.10 mg/eq per 100 g of soil, and for grain-legume crop rotation, slightly increased by 0.45 mg/eq per 100 g of soil.

There was a slight decrease in the content of Mg by the crops in the crop rotation. The amount of exchange Ca for the organo-mineral fertiliser system in grain-legume crop rotation increased by 2.1 mg/eq per 100 g of soil, in specialised grain-legume rotation and legume rotation – 3.28 and 2.51 mg/eq per 100 g of soil (Table 3).

At the end of the second crop rotation, the calcium content increased considerably compared to the beginning of the first grain-legume crop rotation – 8.7%, specialised grain-legume rotation – 9.8%, and in legume rotation by 4.1%, due to the presence of calcium in fertilisers and the rise of carbonates in the upper layers due to the humidification regime.

Several studies (Yashchuk *et al.*, 2016; Skrylnyk *et al.*, 2019) found that the application of manure twice during crop rotation in the amount of 40 tonnes per hectare contributed to an increase in humus content by 7.2%, and the

use of an organo-mineral fertiliser system – by 11.4% compared to the control group. According to the classification of soils by humus content, its level is assessed as high or even very high.

The type of humus is defined as humate and the degree of humification is characterised as high. The nitrogen content of humus is estimated as average.

Table 3. Changes in the physical and chemical parameters of typical chernozems depending on fertiliser systems in the 0-25 soil layer at the end of the second crop rotation

Soil fertilisation system	Salt pH	S, mg/eq per 100 g of soil	Mg/eq per 100 g of soil	Ca, mg/eq per 100 g of soil
Grain-legume crop rotation				
Without fertilisers	7.1	48.02	1.53	17.15
Organo-mineral	7.2	50.15	2.30	19.25
Specialised grain-legume rotation				
Without fertilisers	7.2	48.02	1.42	15.82
Organo-mineral	7.1	48.23	2.20	19.10
Legume rotation				
Without fertilisers	7.1	48.28	1.35	15.50
Organo-mineral	7.2	48.41	2.52	18.01
LSD ₀₅	0.17	2.61	0.51	0.19

Source: developed based on the conducted research

Humins are the most stable compounds of soil organic matter, which gradually transform into carbon-rich compounds over time. It has been established that the organo-mineral fertiliser system creates favourable conditions for the accumulation of stable and decomposition-resistant organic matter compounds in the soil (Skrylnik et al., 2020).

Under the influence of fertilisation systems and crop rotation, changes occur in the fractional composition of both fulvic and humic acids. The use of fertilisation systems leads to an increase in the third fraction of fulvic acids in grain-legume specialised crop rotation, which affects the HA: FA ratio in favour of the humic type of humus formation.

The transformation of typical deep low-humus chernozem depends on the saturation of row and grain crops in crop rotation and fertiliser systems. The organo-mineral fertiliser system helps to increase the humus content in typical deep chernozem. In all crop rotations,

the qualitative composition of humus is transformed towards the redistribution of fractions.

Humus directly or indirectly affects soil fertility and has a considerable impact on the physico-chemical and agrochemical characteristics of typical chernozems, in particular on the overall metabolic acidity, cationic exchange capacity, soil buffering, and nitrogen and phosphorus content. Due to the strong direct correlation between them, an increase in humus content is always perceived as an improvement in these characteristics and overall soil fertility. (Yevtushenko & Tonkha 2017). According to the authors, under the influence of fertilisation, the physico-chemical characteristics of typical chernozem improve. Although the incorporation of straw, cover crops, and mineral fertilizers leads to a slight increase in hydrolytic acidity, it is not considered critical. Intermediate products of straw and cover crop decomposition have an acidic nature, which also contributes to soil acidification. Increasing the input of fresh

organic matter into deeper soil layers promotes the intensive accumulation of semi-decomposed products due to limited oxygen availability for further transformations.

Similar research results were published by Degtyarov *et al.* (2018). It was established that under the control option (without fertilisers) and options with the use of mineral fertilisers ($N_{73}P_{81}K_{84}$) and organic fertilisers (12 tonnes of manure), a high degree of humification of organic substances is observed. Under an organo-mineral fertiliser system (single and one and a half), there is a more intensive accumulation of non-calculated organic substances, as a result of which the soils of these sites have an average degree of humification of organic substances.

H. Hospodarenko *et al.* (2018) found that the fraction-group composition of humus in an opdyzolised chernozem soil, after long-term (50 years) application of different fertiliser rates and fertilisation systems in crop rotation, is characterised by a predominance of humic acids over fulvic acids. This leads to an expansion of Ch to Cf ratio, indicating a humic type of soil. The proportion of humic acids bound to calcium (HA 2) is 18.1-25.4% of total carbon and prevails in the humic acid fraction. The fraction of fulvic acids bound to HA2 (FA2) is 6.1-7.4% of the total carbon and prevails in the fraction of fulvic acids. This indicates that the leached chernozem soil, after long-term and systematic fertiliser application, had a high optical density of humic acids, which is characteristic of soils of the chernozem type.

The proportion of fulvic acids, depending on the experiment variant, was in the range of 13.8-17.2% of the total carbon content in the soil. Under the mineral fertilisation system, the quantity of fulvic acids decreased by 23%, under the organic system by 21%, and under the organo-mineral system by 10-20% compared to unfertilised plots. This indicates that organic fertilisers, both alone and in combination with

mineral fertilisers, are an important factor in increasing the total humus content in the soil, including humic acid groups (Paterson *et al.*, 2016; Baskaran *et al.*, 2017).

The use of mineral fertilisers and acid precipitation leads to the oxidation of organic substances in the soil and causes the decalcification of typical chernozem, which has a genetically neutral reaction. Applying 100 kilogrammes of mineral fertilisers per hectare on a leached chernozem soil reduces the pHKCL level by 0.007 and increases the acidity by 0.42 moles per kilogramme of soil (Smishna-Starinska, 2016). Long-term use of mineral fertilisers has a considerable effect on the acidification of the soil solution (Balaev *et al.*, 2020).

Without the use of land reclamation agents and fertilisers, the use of chernozem soils leads to a decrease in the degree of soil saturation with bases to 85.7%, a decrease in pH, and an increase in hydrolytic acidity. Total calcium and magnesium losses depend on fertiliser doses and soil granulometric composition (Mazur, 2008).

CONCLUSIONS

The increase in the content of qualitative indicators of typical chernozem humus is most positively affected by the organo-mineral fertiliser system, which causes an increase in the proportion of humic acids. At the same time, the carbon fraction of the insoluble residue increases. Chernozem of the control option (without fertilisers) had a sufficient degree of humification of organic substances. Under the condition of using an organo-mineral fertiliser system, there is a less intensive accumulation of non-humified organic substances, as a result of which the soils of these sites have a high degree of humification of organic substances.

The combination of organic matter at a rate of 11.5 tonnes per hectare (8 tonnes of manure and 3.5 tons of by-products) and mineral

fertilisers $N_{27}P_{38}K_{45}$ per hectare resulted in an observed tendency towards an increase in the buffering capacity of the typical chernozem soil type within the crop rotation area.

Crop rotation and the organic-mineral fertilisation system resulted in humus formation of the humic type, with HA:FA ratios of 2.84, 2.41, and 2.53 in the grain-legume, specialised grain-legume, and legume rotations, respectively.

Humus of all research variants has a humane-fulvate type. It is characterised by a high content of free humic acids. Humus of the control options without the use of fertilisers has a low content of humic acids, which are bound to calcium, while the option of the organo-mineral fertiliser system has a high content.

Indicators of physical and chemical properties under the influence of fertiliser improve, although the combined application of mineral and

organic fertilisers contributed to an increase in the amount of absorbent bases. The calcium content increased at the end of the second rotation compared to the beginning of the first rotation of crop rotations. The amount of calcium increased in the organo-mineral fertiliser system in specialised grain-legume rotation and legume rotation. Magnesium considerably increased with the combined application of mineral and organic fertilisers compared to the non-fertilised version. A promising area for further research is the qualitative changes in humus during repeated crop rotations within a short-rotation system.

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CONFLICT OF INTERESTS

None.

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Якісний склад гумусу та фізико-хімічні властивості чорнозему типового залежно від системи удобрення

Анотація. Ґрунтотворний процес тісно пов'язаний з накопиченням і колообігом органічних речовин, які є джерелом елементів живлення для рослин, що вивільняються в процесі мінералізації гумусу, тому актуальним є дослідження щодо визначення показників якісного складу гумусу. У зв'язку з цим метою даного дослідження є визначення гумінових і фульвокислот в чорноземі типовому залежно від системи удобрення. Провідними підходами до вирішення цієї проблеми є проведення польових і лабораторних досліджень для визначення якісних показників гумусу та дисперсійні методи, для визначення точності та достовірності експериментальних даних. В результаті проведених досліджень, встановлено, що за органо-мінеральної системи удобрення збільшується кількість гумінових кислот, проте зростає кількість вуглецю нерозчинного залишку. Застосування органо-мінерального удобрення, відмічено зменшення інтенсивного накопичення негуміфікованих органічних речовин, ґрунти даних ділянок мають підвищений ступінь гуміфікації органічних речовин. Поеднання органічних в нормі 11,5 т (8 т ґною і побічна продукція 3,5 т) і мінеральних $N_{27}P_{38}K_{45}$ на гектар сівозмінної площі спостерігалася тенденція до зростання буферності чорнозему типового, цьому варіанті відбулось зростання ємкості поглинання у кінці другої ротації за зернопросапної сівозміни – на 6,05 мг/екв на 100 г, зернопросапної спеціалізованої – на 3,9 і просапної – на 3,06 мг/екв на 100 г ґрунту порівняно із початком першої ротації сівозмін. За органо-мінерального удобрення зростає третя фракція фульвокислот у зернопросапній

спеціалізованій сівозміні, що впливає на співвідношення ГК:ФК у бік гуманного типу гумусоутворення. Співвідношення гумінових кислот до фульвокислот у зернопросапній сівозміні за органо-мінеральної системи становило 2,84 в кінці другої ротації, на початку першої ротації – 2,24. Матеріали дослідження мають практичне значення для аграріїв при аналізі фракційно-групового складу гумусу чорнозему типового

Ключові слова: гумінові кислоти; фульвокислоти; гумусованість; фракційний склад; система удобрення

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Physico-chemical and agrochemical indicators of typical chernozem and isohumisol under various tillage and fertiliser systems

Abstract. The relevance of examining the physico-chemical and agrochemical indicators of soils lies in the fact that these properties determine the level and quality of agricultural crops, thus affecting the food security of the country as a whole. In this regard, the purpose of the study is to establish the long-term impact of different soil tillage and fertilisation technologies on the profile distribution of physico-chemical and agrochemical indicators of typical chernozem and isohumisol soils. Under conventional tillage (CTu), plant nutrients were evenly distributed within the upper layer of typical chernozem, with the highest values observed in the 10-40 cm depth range. Under soil conservation tillage, with the addition of straw at a rate of 1.2 t/ha + N₁₂ + N₇₈P₆₈K₆₈, the content of available hydrolyzable nitrogen, mobile phosphorus, and exchangeable potassium in the typical chernozem soil was highest in the 0-20 cm layer: 192.30 ± 22.44 and 192.51 ± 22 mg/kg; 63.57 ± 5.762 and 62.07 ± 0.312 mg/kg; 527.14 ± 36.204 and 465.27 ± 5.844 mg/kg for shallow (RTu) and deep (DRTu) soil conservation tillage, respectively. In total at 0-100 cm layer of typical chernozem, the highest content of plant nutrients was observed under DRTu followed by CTu. In Chinese isohumisol, a higher accumulation of NH₄⁺ - N and NO₃ - N was observed in the 0-10 cm depth range under no-till soil management, while in the 20-40 cm depth range, plowing resulted in greater accumulation of these nutrients. The total phosphorus content did not notably change with depth. Under the application of fertilisers, the content of nutrients and the

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reaction value of the medium increased for all tillage treatments of typical chernozem. The content of exchangeable calcium and magnesium did not change considerably on the fertilised inputs. The findings of this study indicate the feasibility of using crop residues with nitrogen compensation and cover crops, in conjunction with mineral fertilizers, to maintain the fertility level of chernozem soils under conditions of limited manure utilisation

Keywords: profile; nutrients; acidity; calcium; magnesium

INTRODUCTION

The Law of Ukraine “On land protection” No. 962-IV (2003, June) and DSTU 4362: 2004 (2015) state that plant nutrition elements, together with other soil indicators and environmental parameters, are mandatory components of soil fertility. Understanding the relationship of nutrients to crop needs, soil properties, the environment, and agrotechnical practices is essential for integrated soil nutrition management and sustainable agriculture in general. According to V.V. Hamaiunova *et al.* (2019) and Kravchenko (2020), the formation of a nutrient regime in soils is achieved through its natural background, microbiological activity, application of organic and mineral fertilisers, as well as micro- and nano-fertilisers. Other contributing factors include mulching, diversification of crop rotations with grasses, legumes, intermediate, compatible, and after-harvest crops, and cover crops. Plants, like all living organisms, need nutrition elements for their growth, development, and fruiting. According to Marchuk (2016), 78 elements out of 92 existing elements in nature and 118 elements of the periodic table were found in dry plant biomass. Nutrients directly affect the life cycle of plants and cannot be replaced by other substances (Karpenko *et al.*, 2022). Nitrogen is required for the synthesis of adenosine triphosphate (ATP), nucleic acids, coenzymes, vitamins, and chlorophyll. Phosphorus is involved in the synthesis of DNA, nucleic acids, phospholipids, and plant

respiration. Potassium is an activator of 60 K⁺/Na⁺ enzymes, proteins, a carrier of carbohydrates, a regulator of water and an anionic-cationic balance in cells. Calcium and magnesium improve the absorption of nutrients by plants, take an active part in the metabolism of chlorophyll, fats, proteins, DNA and RNA, etc. Microelements and trace elements (such as selenium, mercury, cadmium, and lead) play an extremely important biofunctional role in metabolic processes in plants. According to de Mello Prado (2021), the concentration of these elements in plants does not exceed 10⁻³%. The content of nutrients in soils and their availability to plants in agriculture is regulated by the application of fertilisers. Based on the results of a meta-analysis of 2,058 soil samples from different regions of China conducted by Jia *et al.* (2022), the 35-year application of mineral fertilizers combined with manure resulted in the following increases: 0.1 – pH, 67% – organic carbon content, 67% – total nitrogen content, 70% – available hydrolyzable nitrogen, 149% – total phosphorus, 281% – mobile phosphorus. Marchuk (2016) suggests that fertiliser application can increase crop yield by 60% in the Polissya region, 40% in the Forest-Steppe region, 15% in the Moist Steppe region, 10% in the Dry Steppe region, and 40% in the Irrigated Steppe region.

Research conducted by Xomphoutheb *et al.* (2020) indicates that soil tillage also affects the availability of nutrients by stratigraphically

distributing them within the soil profile, along with changes in soil properties. Kayl (2019) and Rymar (2007) found that plowing creates the most favourable conditions for the mineralisation of nutrients and the oxidation of ammonia and ammonium salts in nitric acid salts. Several authors have found that under minimal tillage practices, the content of mineral nitrogen compounds decreases (Zavalyn *et al.*, 2018), mobile phosphorus mobility decreases (Korotkykh and Vlasenko, 2015), and exchangeable potassium decreases (Malhi *et al.*, 2018). The study conducted by Dubovyk *et al.* (2021) on typical chernozem soil demonstrated that the implementation of conservation tillage practices resulted in the following changes: a decrease in pH_{KCl} level, exchangeable calcium content, ammonium and nitrate nitrogen content; and an increase in the content of available hydrolysable nitrogen compounds, mobile forms of phosphorus, and exchangeable potassium in the 0-10 cm soil layer. The opposite pattern of changes in the indicators of typical chernozem was observed in layer 10-20 cm, where plowing prevailed. Sithole *et al.* (2019) observed the effect of stratification on the surface concentration of nutrients, organic matter, and pH in soils under the application of no-till and minimal tillage practices. However, the latest studies still do not provide information on the long-term impact of various agrotechnical measures on changes in the physico-chemical environment in soil profiles. The purpose of this study is to identify the influence of tillage and fertiliser technologies on the stratigraphic distribution of physico-chemical and agrochemical properties in the profiles of typical chernozem and isohumisol. The research hypothesis states that fertilisation increases the content of nutrients in soils and alters the environmental pH. Moreover, reducing tillage depth leads to an increase in nutrient concentration near the soil surface.

MATERIALS AND METHODS

Field experimental studies on typical chernozem soil were conducted at the stationary research site of the Department of Soil Science and Soil Conservation named after M.K. Shykula at NUBiP, Ukraine, at the Velikosnitinske educational and research farm named after O.V. Muzichenko, located in the village of Velika Snitynka, Fastiv district, Kyiv region (50°5'N, 30°2'E). The experiment was conducted in 1998-2022 using the method of split sections with an elementary section size of $6 \times 30 = 180 \text{ m}^2$. The system of primary soil tillage consisted of the following variants: shallow minimum tillage (RTu) to a depth of 10-12 cm for all crops; deep minimum tillage (DRTu) to a depth of 25-27 cm for root crops and 20-22 cm for cereal crops; plowing (CTu) to a depth of 25-27 cm for root crops and 10-12 cm for cereal crops. The crop rotation sequence that was studied consisted of the following crops: soybean, winter wheat, grain corn, barley, grain corn. The average amount of fertilisers per 1 ha of crop rotation area met the following standards: 1. Control (without fertilisers); 2. Straw 1.2 t/ha + $\text{N}_{12} + \text{N}_{78}\text{P}_{68}\text{K}_{68}$; 3. Straw 1.2 t/ha + N_{12} + cover crops + $\text{N}_{78}\text{P}_{68}\text{K}_{68}$.

Field experimental studies on isohumisol were conducted at the National Research Station for Soil and Water Management and Conservation. The station is located in the town of Guangrong, 10 km away from the city of Hailun in Heilongjiang Province, China (47°36'N, 126°83'E). This research station is a structural unit of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences. The station was put into operation in 2006. The field stationary single-factor experiment was established in 2004 using the split-plot design method. The elementary plot size was 4.5×20 metres, resulting in an area of 90 square metres. The main plot size was 50 square metres. The experiment was repeated three times. The basic

tillage system was presented with the following options: 1. The ridge tillage (CT) was conducted to a depth of 27-30 cm for all crops. The minimum tillage (RT) was conducted to a depth of 25 cm for all crops; 2. No-till (NT). The fertiliser rate was: $N_{69,5}P_{51,75}K_{15} + N_{100}CO(NH_2)_2$ – for corn grain and $N_{20,25}P_{51,75}K_{15}$ – for soybean. The scheme of crop sequence in a short-term crop rotation consisted of two crops: soybeans and corn grain.

Soil sampling was conducted according to: DSTU ISO 10381-1:2004, DSTU ISO 10381-2:2004. To determine the overall quality of the soil and its chemical and physical properties, composite soil samples were collected from each plot using a manual soil auger at depths of 0-5, 5-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm. Mixed soil samples taken in the field were examined in three replications in the laboratory.

In the typical chernozem soil of the research field “Velykosnitynske” at NUBiP, the mobile forms of phosphorus and potassium were determined using the modified Machigin method (DSTU ISO 4114-2002, 2002). The available hydrolysable nitrogen was measured using the Kornfeld method (DSTU 7863:2015, 2016). The pH in potassium chloride (pH_{KCl}) was determined according to DSTU ISO 10390:2007 (2016). The exchangeable calcium and magnesium were analysed following DSTU 7861:2015 (2016).

The content of total phosphorus, ammonium, and nitrate nitrogen in samples of Chinese isohumisol was determined on an automatic flow analyser Skalar San Plus (Breda, Netherlands). Preparation of soil samples for the analysis of ammonium and nitrate nitrogen, according to DSTU 4729:2007 (2008), involved the extraction from the soil using a 1% potassium sulfate (K_2SO_4) solution in a soil-to-extractant ratio of 1:5. When determining NO_3-N , the following reagents were used (per 1 litre of solution): 1. NH_2SO_3H (5 g) + Brij 35(1 ml); 2. NH_4Cl (50 g) + Brij 35 (1 ml) + $NH_3 \cdot H_2O$ (1 ml);

3. HCl (100 ml) + $C_6H_8N_2O_2S$ (10 g) + $C_{12}H_{16}Cl_2N_2$ (0.5 g). When determining NH_4-N – the following reagents were used (per 1 litre of solution): 1. $C_4H_4O_6KNa$ (33 g) + $C_6H_5O_7Na_3 \cdot 2H_2O$ (24 g) + Brij 35 (3 ml) + 1M Hd; 2. $NaOH$ (25 g) + $C_7H_5NaO_3$ (80 g); 3. $Na_2[Fe(CN)_5NO] \cdot 2H_2O$ (1 g); 4. $C_3N_3O_3Cl_2Na \cdot 2H_2O$ (2 g). Determination of the total phosphorus content was conducted considering the preparation of soil samples for analysis according to DSTU 4290:2004 (2005). When determining the total phosphorus – the following reagents were used (per 1 litre of solution): 1. H_2SO_4 (85 ml 95-97% H_2SO_4) + $H_2S_2O_8$ (9.9 g); 2. H_2SO_4 (160 ml 95-97% H_2SO_4) + FFD6 (2 mL); 3. $NaOH$ (230 g); 4. FFD6 (2 ml); 5. H_2SO_4 (40 ml 95-97% H_2SO_4) + $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ (4.8 g) + FFD6 (2 ml); 6. $C_6H_8O_6$ (4.5 g) + FFD6 (5 ml); 7. $K(SbO)CuH_4O_6 \cdot 1/2H_2O$ (300 mg). The samples were introduced into the instrument using the SA1150 sampler, which was controlled both by a computer and manually using the corresponding software called “FlowAccess™ software”. During the research, various operations were employed, including addition, mixing, distillation, dialysis, ion exchange, heating, UV combustion, and others. For the determination of sample indicators, fluorescent two-channel single-beam detectors, detectors for flame photometry, and NP analysers for mineral soils with a combustion block were utilised.

The arithmetic means of the results, significant differences, and the level of significance were determined using software such as Microsoft Excel 2016, IBM SPSS Statistics for Windows v. 20.0 (© SPSS, Chicago, Illinois), and SigmaPlot for Windows Version 14.0 (2017 Systat Software, Inc.). The average values shown in the figures with different lowercase letters indicate a significant difference between the tillages, and large letters indicate a significant difference between the soil layers. To compare the average values, the Student's t-test was used at the significance

level $\alpha=0.05$. The Bonferroni method was used to correct the errors of multiple comparative samples of a one-way ANOVA analysis.

RESULTS AND DISCUSSION

The results of the studies presented in Fig. 1-6 show that the main influence of different tillage on the nutrient regime is associated with the stratigraphic arrangement of nutrients in different layers of chernozems against the backdrop of changes in the reaction of the soil environment. The soil environment reaction is determined by

the balance of active hydrogen and hydroxide ions in the soil solution or exchangeable state of the soil-absorbing complex. Chernozems are soils with a high level of buffer capacity, which is provided by a variety of exchangeable cations, among which calcium and magnesium are dominant. According to the grading of soils by pH of salt extract (DSTU 4362: 2004, 2015), typical chernozem is characterised by a neutral to near-neutral soil reaction in the 0-50 cm layer (6.74-7.49) and slightly alkaline (7.51-7.82) in the 50-100 cm layer (Fig. 1).

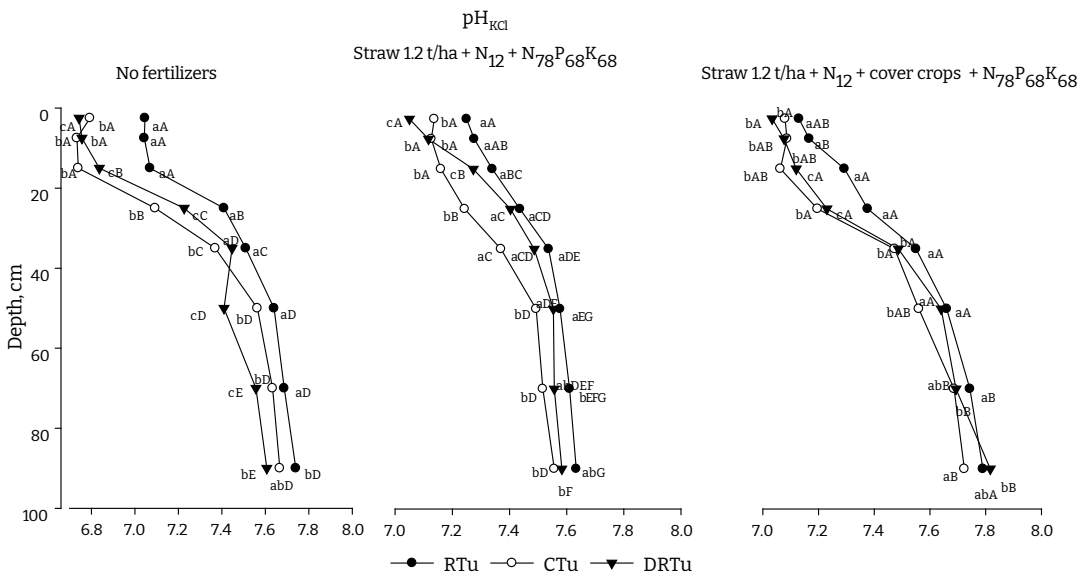


Figure 1. Profile changes in pH in typical chernozem under shallow minimum tillage (RTu), plowing (CTu) and deep minimum tillage (DRTu)

The level of exchangeable acidity of typical chernozem increased from the upper to lower horizons under all variants of tillage and fertilisation. pH_{KCl} in 0-5, 5-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm layers were:

1) 7.05; 7.04; 7.07; 7.41; 7.51; 7.64; 7.69 and 7.74 – for RTu, 6.79; 6.73; 6.74; 7.09; 7.37; 7.56; 7.63 and 7.67 – for CTu, 6.74; 6.76; 6.84; 7.23; 7.45; 7.41; 7.56 and 7.61 – under DRTu in the non-fertilised variant;

2) 7.25; 7.28; 7.34; 7.44; 7.54; 7.58; 7.61 and 7.63 – for RTu, 7.14; 7.13; 7.16; 7.24; 7.37; 7.49; 7.52 and 7.56 – under CTu, 7.05; 7.12; 7.27; 7.40; 7.49; 7.55; 7.56 and 7.58 – under DRTu in the version with the application of straw 1.2 t/ha + $N_{12} + N_{78}P_{68}K_{68}$;

3) 7.13; 7.17; 7.29; 7.38; 7.55; 7.66; 7.74, and 7.79 – under RTu, 7.08; 7.09; 7.06; 7.20; 7.47; 7.56; 7.69, and 7.72 – under CTu, 7.03; 7.08; 7.12; 7.23; 7.49; 7.64; 7.69, and 7.82 – under DRTu with the addition of

straw 1.2 t/ha + N₁₂ + cover crops + N₇₈P₆₈K₆₈. On average for the 0-100 cm layer, the highest pH_{KCl} value was noted for RTu: 7.39 ± 0.024; 7.46 ± 0.024 and 7.46 ± 0.025 vs. 7.20 ± 0.025; 7.33 ± 0.020 and 7.36 ± 0.022 – for CTu, 7.20 ± 0.024; 7.38 ± 0.030 and 7.39 ± 0.020 – for DRTu in variants “1”, “3”, and “5” respectively. Fertilisation considerably increased the level of exchangeable acidity in 0-5, 5-10, and 10-20 cm layers by: 1) 0.20; 0.23, and 0.27 – under RTu, 0.34; 0.39, and 0.42 – under CTu, 0.31; 0.36, and 0.44 – under DRTu with the application of straw 1.2 t/ha + N₁₂ + N₇₈P₆₈K₆₈ and 0.08; 0.12, and 0.22 – under RTu, 0.29; 0.35, and 0.32 – under CTu, 0.29; 0.32, and 0.28 – under DRTu with the application of straw 1.2 t/ha + N₁₂ + cover crops + N₇₈P₆₈K₆₈. A significant increase in pH_{KCl} was observed in the lower part of the soil profile under DRTu with fertilisation.

The use of ammonium nitrate on typical chernozem temporarily reduced pH values, which is confirmed by Raza *et al.* (2020). According to Tian *et al.* (2015) and Hao *et al.* (2020), the use of excessive doses of nitrogen fertilisers in arable soils reduced the pH level by 0.5 units – in China and 0.26 – in the whole world. The highest pH values in the upper 0-10 cm layer were observed in the fertilised version without the use of cover crops and the version without fertilisers. The use of cover crops in conjunction with the straw application of 1.2t/a + N₁₂ + N₇₈P₆₈K₆₈ resulted in a decrease in pH by 0.1-0.4 units in all treatments and brought the soil pH closer to a neutral level. According to Adekiya *et al.* (2019), the increase in acidity due to the use of cover crops is associated with the formation of organic acids and the release of CO₂ when decomposing organic residues. Some of the calcium and magnesium carbonates are used to neutralise the newly formed active hydrogen. Tillage changes the redox regime of soils thus affecting H⁺ and OH⁻ system dynamics: soil-plant-soil solution. During plowing,

the upper fertile layer undergoes more intense oxidation, as a result of which the organic matter of the soil is mineralised, functional groups of an acidic nature are released, which dissociate in the soil solution to form active hydrogen. The pH level for CTu was lower compared to RTu and DRTu by 0.1-0.4 and 0.1-0.3-with the use of straw 1.2 t/ha + N₁₂ + N₇₈P₆₈K₆₈ and 0.1-0.6 and 0.1-0.2 – with the use of straw 1.2 t/ha + cover crops + N₁₂ + N₇₈P₆₈K₆₈ accordingly. In more humid conditions created by the no-tillage soil management, denitrification processes are intensified, leading to the release of OH⁻ ions into the soil solution and consequently increasing the soil pH (Jugsujinda *et al.*, 1977). The application of shallow minimum tillage significantly increased the pH values measured with KCl in the top 0-5 cm soil layer, ranging from 7.05 to 7.25. In comparison, CTu showed pH values ranging from 6.79 to 7.14, and under DRTu pH values ranged from 6.74 to 7.05. In general, the lowest pH_{KCl} was observed in the unfertilised variant, while the highest level was recorded in the variant with the straw application at a rate of 1.2 t/ha + N₁₂ + N₇₈P₆₈K₆₈. In a 0-40 cm layer, the variant with the use of cover crops occupied an intermediate position between the variants “1” and “3” in terms of pH_{KCl} values.

Zavalyn *et al.* (2018) consider that typical chernozems, among other soils, have the highest content of mineral and available hydrolysable nitrogen (exchangeable nitrogen, free and absorbed ammonia, amides, partially amino acids, aminosugars, and other organic compounds). The nitrogen content is primarily influenced by the soil's humus reserves, the proportion of labile fractions of humic and fulvic acids, and the decrease in the C:N ratio. In the presented studies, the content of available hydrolysed nitrogen compounds depended on the tillage and fertiliser inputs, and depth of the sampling (Fig. 2).

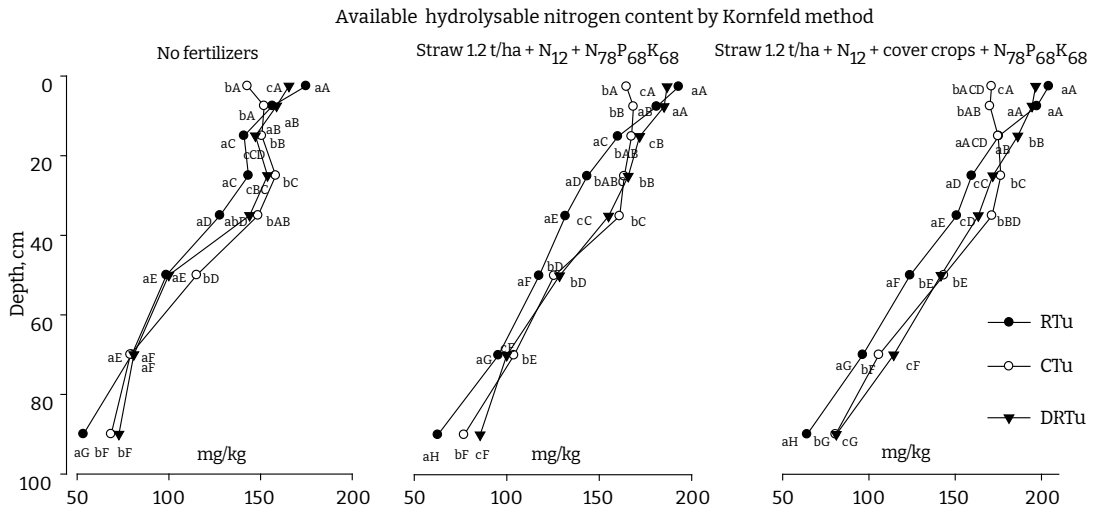


Figure 2. Profile changes in the content of available hydrolysable nitrogen compounds in typical chernozem under the use of shallow minimum tillage (RTu), plowing (CTu) and deep minimum tillage (DRTu)

The increased and average content of available hydrolysed nitrogen in the arable horizon gradually decreased to low and very low levels in layers of 60-80 and 80-100 cm, respectively. The lowest content of available hydrolysed nitrogen was in the version without the use of fertilisers and was: 174.82-53.40; 142.86-68.51, and 165.47-72.75 mg/kg – under RTu, CTu, and DRTu, respectively. The application of fertilisers increased the content of available hydrolysable nitrogen in the following ranges: 24.60-0.12; 24.87-5.30; and 28.59-11.02 mg/kg for RTu, CTu, and DRTu in the “3” treatment, respectively. In the “5” treatment, the ranges were 40.83-10.78; 28.28-12.22; and 41.82-8.37 mg/kg, respectively. According to Vilakazi *et al.* (2020), under the application of nitrogen fertilizers at the rates of N₆₀, N₁₂₀, and N₂₄₀ in clay soil (Hutton) in South Africa the content of ammonium and nitrate nitrogen in the soil increased. It also accelerated the nitrogen mineralisation rate, with the highest respective coefficients observed for plowing. In the research conducted, intensive oxidation of humus substances occurred in the

upper 0-10 cm layer of the typical chernozem soil during plowing, leading to a decrease in alkaline-soluble nitrogen compounds under this tillage practice. Therewith, this method of tillage accumulated more available hydrolysed nitrogen compounds in the layer of 20-40 cm – 153.43-173.91 mg/kg under CTu against 135.65-155.26 mg/kg – under RTu and 148.91-167.61 mg/kg – under DRTu. The increase in plant root mass in the lower soil layers under plowing and deep tillage practices contributed to the enhancement of rhizospheric and microbiological effects. This led to an increase in CO₂ content, the formation of a specific soil moisture and oxygen regime. All of these factors influenced the gradual decrease in available hydrolyzable nitrogen with depth under these tillage practices. A similar effect was observed by Purwanto and Alam (2020) and Li *et al.* (2016) in arable soils of the humid tropics and northern China, respectively. On average, in the 0-100 cm soil layer of typical chernozem, the plowing variant accumulated lower levels of available nitrogen compounds compared to the non-plowing

tillage practices, both in unfertilised and fertilised variants. In the 0-20 cm soil layer of typical chernozem, the non-plowing tillage practices resulted in the highest levels of available hydrolyzable nitrogen compounds: 157.44-192.30 mg/kg for RTu and 157.13-192.51 mg/kg for DRTu, compared to 148.47-172.05 mg/kg for CTu. These technologies create optimal conditions for the concentration of mineral fertilisers, the accumulation of plant residues, their mineralisation products, microbial biomass, and fixed atmospheric nitrogen in the near-surface layer of the soil. With minimum tillage, the mineralisation of organic matter occurs in colder and wetter conditions than under plowing, resulting in relatively slow and prolonged nitrogen mineralisation, thus feeding crops throughout the growing season.

Phosphorus is an important macronutrient of plant nutrition. Under the influence of geochemical and biological processes, phosphates are transformed and translocated in soils (Cross & Schlesinger, 1995), which leads to the formation of water-soluble, labile, and stable phosphates. The chemical equilibrium between labile

and stable phosphates in soils is weaker than between water-soluble and labile (Larsen, 1967). Phosphorus readily reacts with ions of polyvalent and alkaline earth metals, forming sparingly soluble and insoluble salts, which leads to a reduction in the content of mobile phosphorus from applied fertilisers. The content of phosphates, according to Tate and Salcedo (1988), does not depend on redox reactions and corresponding enzymes involved in the transformation of aromatic humus compounds. Therewith, the findings of Ohno and Erich (1997) suggest that plant residues entering the soil through the application of soil conservation technologies can hinder the adsorption of phosphates by planar mineral surfaces and initiate the activation of enzymatic and microbiological activity, which promotes an increase in the content of mobile phosphates.

Different use of typical chernozem affected the provision of plants with mobile forms of phosphorus. The content of mobile forms of phosphorus was highest in the upper layer of typical chernozem (49.88-67.63 mg/kg) and lowest in the layer of 80-100 cm (16.28-21.56 mg/kg) (Fig. 3).

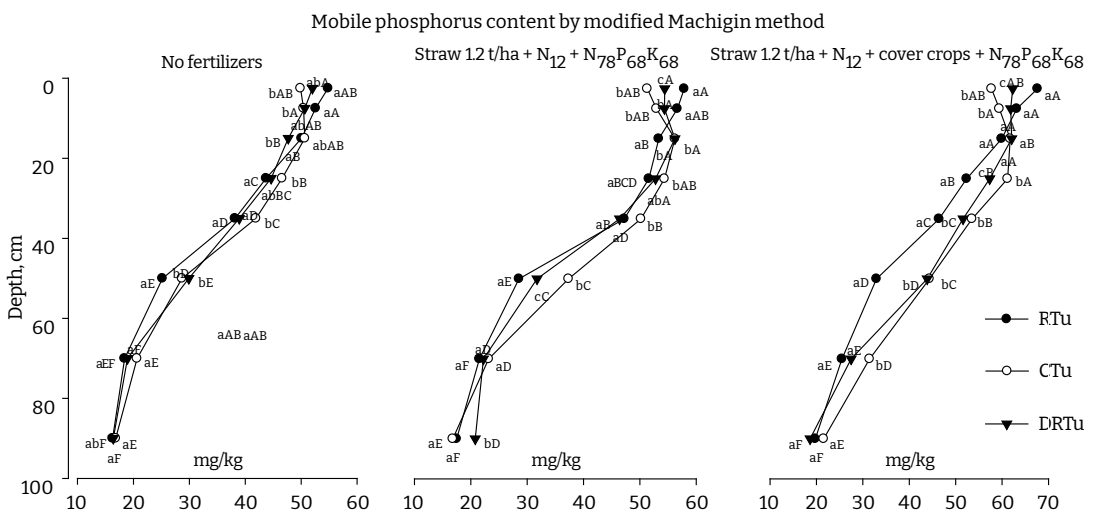


Figure 3. Profile changes in the content of mobile phosphorus compounds in typical chernozem for the use of shallow minimum tillage (RTu), plowing (CTu) and deep minimum minimum tillage (DRTu)

In the upper part of the profile, the content of mobile phosphorus was influenced by the organic matter content and was highest in the case of shallow tillage in the 0-10 cm layer, both in fertilized and unfertilized (control) plots: 54.81-67.63 mg/kg under RTu, compared to 49.88-57.72 mg/kg under CTu, and 52.01-62.28 mg/kg under DRTu. The plowing option considerably increased the content of mobile phosphates in a layer of 20-40 cm compared to other tillage technologies. The application of fertiliser increased the content of mobile phosphates in the arable layer by 3.06-12.83 mg/kg – under RTu, 1.45-11.12 mg/kg – under CTu, and 2.41-14.38 mg/kg – under DRTu. In a layer of 50-100 cm, the content of the above-mentioned element notably increased under CTu and DRTu. Hanhur *et al.* (2022) also observed the stratification effect of no-till, mini-till, and shallow tillage on the accumulation of mobile phosphorus in typical chernozem. The addition of cover crop straw (variant 5) increased the content of mobile phosphorus by 3.0-16.7 mg/kg compared to the variant without cover crops (variant 3), and by 5.5-40.5 mg/kg compared to the control (variant 1). On the other hand, Damon *et al.* (2014) did not find a significant effect of grain straw on the level of mobile phosphate supply. It can be stated that the application of complete mineral fertiliser with nitrogen compensation and sowing of cover crops (variant 5) creates optimal conditions for the transformation of plant residues by microorganisms. Selles *et al.* (1997) determined that the higher content of organic phosphates during minimum tillage is also associated with the slow decomposition of plant residues, which prevents their rapid mineralisation losses and leaching into the lower layers of the soil. According to Reed *et al.* (2011) and in line with the obtained X-ray structural analysis data of typical chernozem (data not shown), the stabilisation of mobile phosphorus under soil

conservation tillage, compared to conventional tillage, is determined by the higher sorption capacity of the soil and a larger specific surface area of weathered secondary minerals (layered silicates, amorphous oxides, and metal hydroxides). Mallarino and Pecinovsky (2006), who studied the 7-year impact of different soil tillage technologies on the content of mobile phosphorus and exchangeable potassium in “Floyd” and “Clyde” soils in the state of Iowa, found the largest stratification effect under no-till and minimum tillage, and the smallest effect under chiselling and conventional tillage. Additionally, exchangeable potassium was distributed more evenly throughout the profile compared to phosphorus, which can be attributed to the increase in total potassium reserves with depth in soils formed on forest parent material.

Overall, soil gross potassium reserves are 5-50 and 8-40 times higher than nitrogen and phosphorus reserves, respectively (Yahodyn *et al.*, 1989). According to Myneev (1999), high gross potassium reserves in chernozems can fully provide the planned level of the yield of agricultural crops. However, only 0.5-1.2% of total potassium reserves are in the form of water-soluble and exchangeable compounds (Tsentylo, 2019). According to the classification approach proposed by Pukhal'skaia *et al.* (2009), the exchangeable potassium investigated in the study is categorised into: intensively exchangeable (active), extensively exchangeable (potential), and easily mobile (extracted with CaCl₂ solution). The content of exchangeable potassium in the profile of typical chernozem gradually decreased from the upper layers (400-552.27 mg/kg) to the lower layers (270.06-293.07 mg/kg), with the highest values observed for shallow minimum tillage in the 0-10 cm layer, both in fertilized and non-fertilized (control) plots: 427.23-552.27 mg/kg, compared to 415.70-465.22 mg/kg under CTu and 400.40-468.10 mg/kg under DRTu (Fig. 4).

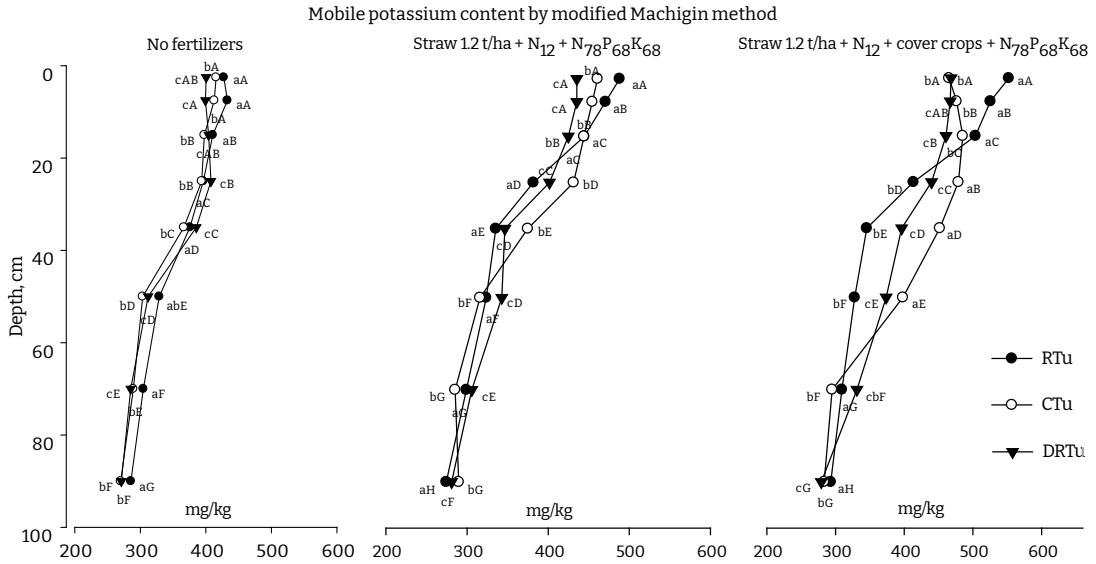


Figure 4. Profile changes in the content of mobile potassium compounds in typical chernozem soil under shallow minimum tillage (RTu), plowing (CTu) and deep minimum tillage (DRTu)

The lowest content of mobile potassium in the above-mentioned layer was noted for DRTu, the variant with CTu occupied an intermediate position. Under plowing, the content of exchange potassium was notably higher than other tillage technologies in a layer of 20-40 cm. The findings of Kumar *et al.* (2022) support these results, as they observed the highest content of exchangeable potassium in Inceptisols after 8 years of no-till practices, compared to conventional tillage and rotational soil management. Nevertheless, Salahin *et al.* (2021) did not find a significant difference in the impact of no-till, conventional tillage, strip tillage, and ridge tillage on the redistribution of exchangeable potassium at depths of 0-5 cm, 5-10 cm, and 10-15 cm in the cultivation of rice, lentils, and jute. On the other hand, substantial effects on increasing exchangeable potassium in loamy calcareous soils were observed with the application of mulching and incorporation of plant residues as the primary soil management practices. The use of

fertiliser increased the content of exchange potassium in the arable layer by 33.94-125.04 mg/kg – under RTu, 41.74-87.70 mg/kg – under CTu, and 20.73-67.70 mg/kg – under DRTu. In a layer of 50-100 cm, the content of this element significantly increased under CTu and DRTu. The effectiveness of applying high rates of potassium (K_{200} , K_{400} and K_{600}) in increasing the yield of sweet potato variety on loamy soils in Nigeria was noted by Essien *et al.* (2023). The results of the study by Xu *et al.* (2020) showed that the positive effect of potassium on increasing crop yield is associated with its synergistic interaction with nitrates, as potassium enhances the metabolism, synthesis of amino acids, and proteins in the presence of nitrogen.

The total proportion of calcium (78-90%) and magnesium (7-19%) in the exchangeable cations of typical chernozems is 85-97% (Polupan, 1988). The highest calcium content is found in soils formed from the weathering products of limestone. In soils, calcium acts as a coagulator of colloidal humus compounds, a stabiliser of

the soil-absorbing complex and soil aggregates, and forms the physical and chemical environment of soils. Calcium and magnesium are used by plants as elements of nutrition, they affect the availability of mobile compounds in soils, and are part of the organic substances of plants. Calcium and magnesium carbonates have a high sorption capacity for phosphate ions, leading to the formation of corresponding salts, hydroxyapatite, and octacalcium phosphate in soils.

Research has shown that the upper humus horizon typically has higher levels of exchangeable calcium and magnesium (Figure 5-6). With depth, the proportion of exchange forms of these cations decreases and the content of insoluble compounds increases accordingly. The lowest values of exchangeable calcium were observed under conventional tillage (20.3-23.1mmol/100 g) compared to RTu (20.8-24.2 mmol/100 g) and DRTu (21.0-24.0 mmol/100 g) (Fig. 5).

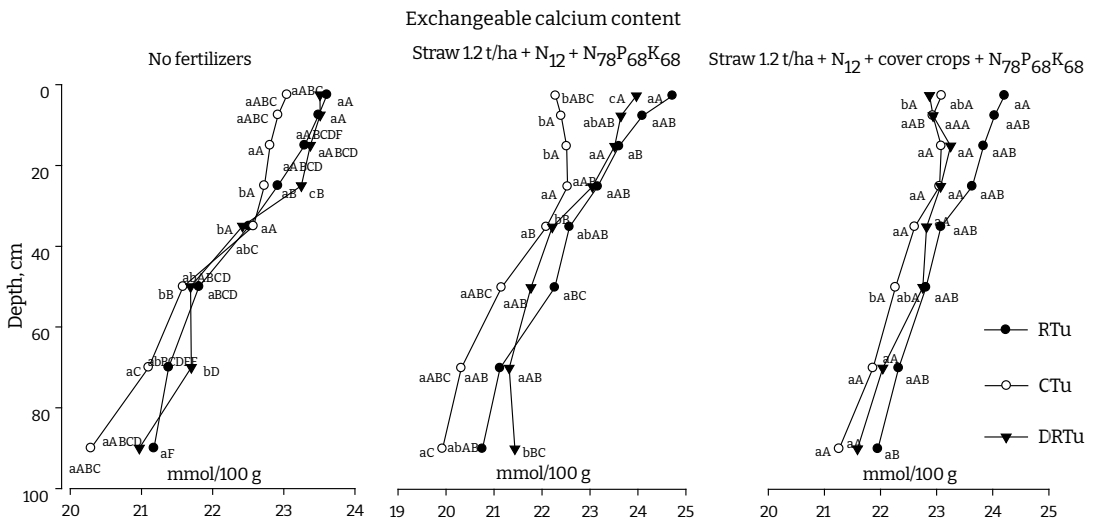


Figure 5. Profile changes in exchangeable calcium content in typical chernozem soil under the use of shallow minimum tillage (RTu), plowing (CTu) and deep minimum tillage (DRTu)

Under deep minimum tillage, the accumulation of exchangeable magnesium was the highest in the 0-20 cm layer of typical chernozem soil, ranging from 3.9 to 4.3 mmol/100 g. This was comparatively higher than the values observed under plowing and shallow minimum tillage, which ranged from 3.8 to 4.1 mmol/100 g (Fig. 6).

Stankowski *et al.* (2022) observed no significant difference in the impact of no-till, minimal tillage, and conventional tillage on the content of exchangeable magnesium in the lower layers of sandy loam brown soil in Pomerania. On the experimental plots where cover crops were used in combination with straw at a rate of 1.2 t/

ha + N₁₂ + N₇₈P₆₈K₆₈, a higher content of exchangeable calcium was observed, while in the fertilized variant without cover crops, there was a higher content of exchangeable magnesium in the 0-20 cm soil layer. There was no considerable difference between the control (without fertilisers) and the fertilised variants in terms of the content of exchangeable potassium and magnesium.

The content of ammonium and nitrate nitrogen and total phosphorus in Chinese isohumisol decreased with depth, depending on the methods of tillage, but there was no statistically significant difference between the studied variants (Fig. 7).

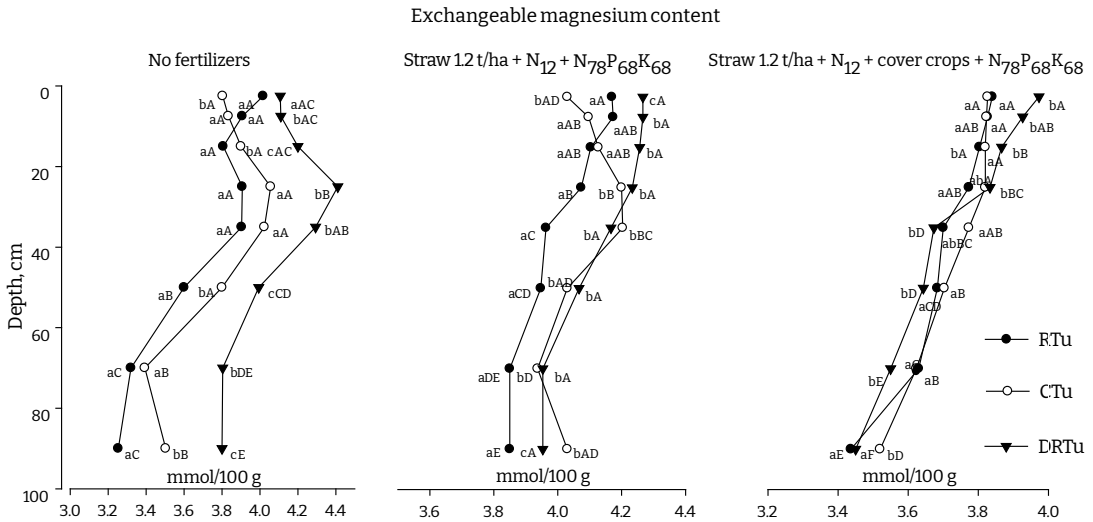


Figure 6. Profile changes in the content of magnesium exchange in typical chernozem under the use of shallow minimum tillage (RTu), plowing (CTu) and deep minimum tillage (DRTu)

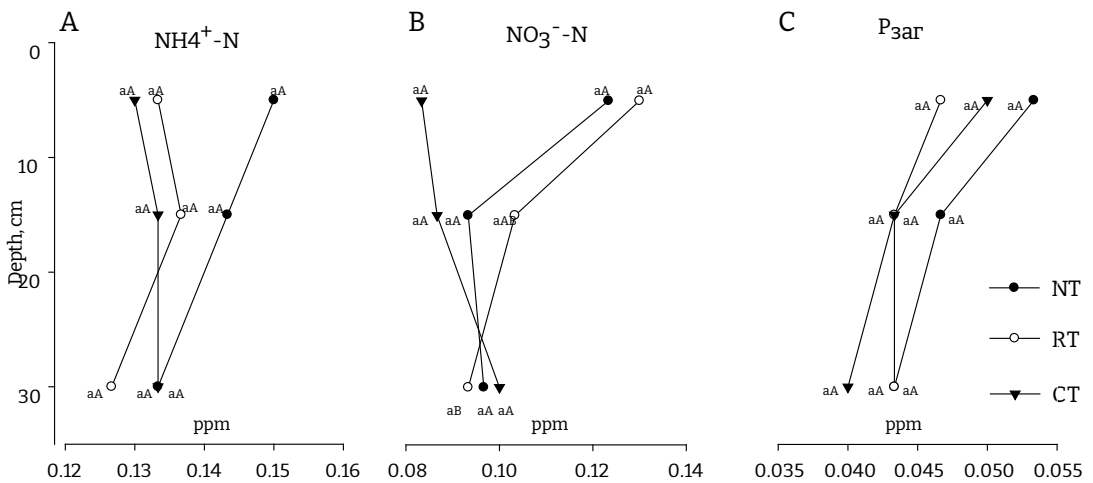


Figure 7. The content of exchangeable $\text{NH}_4\text{-N}$ (A) and $\text{NO}_3\text{-N}$ (B) and total phosphorus (C) in isohumic soil under the use of no-till (NT), minimum tillage (RT), and conventional tillage (CT)

The highest accumulation of $\text{NH}_4\text{-N}$ (0.15 ± 0.015 ppm), $\text{NO}_3\text{-N}$ (0.13 ± 0.015 ppm), and P_{total} (0.05 ± 0.023 ppm) was observed in the 0-10 cm soil layer for the NT, RT, and NT respectively. No-tillage techniques resulted in a higher accumulation of soil organic matter and promoted ammonification and nitrification processes, accompanied by increased enzymatic

and microbiological activity. The total phosphorus content gradually decreased with depth in all tillage options. The highest accumulation of nutrients was observed in the 10-20 cm soil layer for the NT and RT treatments. In the 20-40 cm soil layer, the data obtained did not show notable differences between the tillage treatments. Most phosphates accumulated in no-till due to the

high humus content and minimal erosion losses of the surface layer of isohumisol in this variant.

CONCLUSIONS

Fertilisation and the application of different soil cultivation technologies influenced the soil pH, accumulation of nutrients, and their stratigraphy in the profiles of both typical chernozem and isohumisol. Typical chernozem soil has a neutral to slightly alkaline pH in the upper and subsoil layers and becomes weakly alkaline in the 50-100 cm layer. The lowest pH level of the salt extract was observed in the 0-20 cm layer under the variant without fertilizers, ranging from 6.73 to 7.07. The highest pH level was recorded under the variant with the addition of straw at a rate of 1.2 t/ha + N₁₂ + N₇₆ P₆₆ K₆₆, ranging from 7.05 to 7.34. With depth, the pH increased for all tillage and fertiliser options and acquired maximum values (7.72-7.79) in the fertilised variant with the use of cover crops. The highest pH level of salt extraction was under minimum tillage throughout the profile.

The increased and high content of nutrients in the arable layer gradually decreased to medium, low, and very low levels in the lower layers. Under no-till, there was a greater accumulation of nutrients in the 0-10 cm layer, while under plowing, there was a higher accumulation in the 20-40 cm layer. The content of available hydrolysed nitrogen and exchangeable potassium during shallow minimum tillage on fertilised variants rapidly decreased from a depth of 20 cm. The application of fertilizers and the use of cover crops increased the content of available hydrolyzable nitrogen, mobile phosphorus, and potassium in the 0-20 cm layer as follows: 11.15-24.60 mg/kg, 3.06-12.83 mg/kg, and 33.94-

125.04 mg/kg for RTu; 1.65-21.87 mg/kg, 1.45-11.12 mg/kg, and 41.74-87.70 mg/kg for CTu; and 9.46-26.37 mg/kg, 2.41-14.38 mg/kg, and 20.73-67.70 mg/kg for DRTu, respectively.

The content of exchangeable calcium and magnesium was highest in the upper layer and gradually decreased with depth. The highest calcium content was observed for RTu, while the highest magnesium content was observed for DRTu. On average, no considerable difference was observed between the control (without fertilisers) and the fertilised variants in the 0-100 cm soil layer.

Typical chernozems and isohumisols, being under agricultural use for a long time, have changed their physico-chemical and agrochemical properties. Unfortunately, most researchers predominantly study soil samples collected once a year and prepared for analysis from the upper 0-20 cm soil layer, without considering the profile changes that result from the impact of anthropogenic and natural factors as well as soil formation processes. Studying the profile annual material flows in deep soil layers allows understanding the fundamental changes in soil properties during their agricultural use and helps in managing their fertility. Thus, there arises an urgent need for further research on the impact of conventional agricultural cultivation techniques on agrogenesis and profile changes in the properties of soils of chernozem formation with deep organic matter and nutrient content.

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CONFLICT OF INTERESTS

None.

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Фізико-хімічні й агрохімічні показники чорнозему типового та ізогумусолу за різних систем обробітку ґрунту й удобрення

Анотація. Актуальність вивчення фізико-хімічних й агрохімічних показників ґрунтів пов'язана з тим, що дані властивості визначають рівень та якість врожаю сільськогосподарських культур, впливаючи таким чином на продовольчу безпеку країни в цілому. У зв'язку з цим, метою представлених досліджень було визначення довготривалого впливу різних технологій обробітку ґрунту і удобрення на профільний розподіл показників фізико-хімічних й агрохімічних властивостей чорнозему типового та ізогумусолу. За полицевого обробітку ґрунту (СТu) елементи живлення гомогенізовано розподілялись в орному шарі чорнозему типового і набували найбільших значень у шарі 10-40 см. За ґрунтозахисного обробітку ґрунту, на фоні соломи $1,2 \text{ т/га} + \text{N}_{12} + \text{N}_{78}\text{P}_{68}\text{K}_{68}$, уміст легкогідролізного азоту, рухомого фосфору і обмінного калію у чорноземі типовому був найбільшим у шарі 0-20 см: $192,30 \pm 22,44$ і $192,51 \pm 22$ мг/кг; $63,57 \pm 5,762$ і $62,07 \pm 0,312$ мг/кг; $527,14 \pm 36,204$ і $465,27 \pm 5,844$ мг/кг – за мілкого (RTu) і глибокого (DRTu) безполицевого обробітку ґрунту відповідно. В цілому у 0-100 см шарі чорнозему типового, найбільший уміст елементів живлення був за DRTu і СТu відповідно. У китайському ізогумусолі у шарі 0-10 см нагромаджувалось більше $\text{NH}_4^+\text{-N}$ та $\text{NO}_3\text{-N}$ за безполицевого обробітку ґрунту, у 20-40 см шарі – за оранки. Уміст загального фосфору достовірно не змінювався з глибиною. За внесення добрив збільшувався уміст поживних елементів і величина реакції середовища за усіх варіантів обробітку чорнозему типового. Уміст обмінних кальцію і магнію суттєво не змінювався на удобрених варіантах. Результати проведених нами досліджень вказують на доцільність застосування на полі решток зернових культур з азотною компенсацією та сидератами на фоні мінерального удобрення для підтримання рівня родючості чорноземів в умовах дефіциту використання гною

Ключові слова: профіль; елементи живлення; кислотність; кальцій; магній

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Magnetic susceptibility of inclined soils and its relationship with some agronomic indicators

Abstract. The modern agricultural complex requires the use of new methods for determining soil characteristics for adequate information support of the latest technologies, which is often impossible to provide using conventional methods. The purpose of the study is to identify the informative value of magnetometric methods in determining slope processes that regulate the use of certain measures to increase soil fertility and protect soils from erosion. The study was conducted on inclined agricultural landscapes of the Kharkiv region. This study used a KLY-2 Kappabridge (Czech Republic) and an Ohaus

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403 laboratory scale to determine magnetic susceptibility. The selected soil samples, in accordance with the accepted methods, were brought to an air-dry state under normal conditions. Soil sampling was conducted from a layer of 0-20 cm. Visualisation of the study results and determination of potential soil losses (USLE model) was performed in the QGIS programme. The correlation of magnetic susceptibility on simple and complex slopes was analysed. It was established that on simple slopes, the value of the magnetic susceptibility of the soil has a high value of this indicator with the content of physical clay and organic carbon. Therewith, there is a high degree of connection of this indicator with the results of mathematical modelling of erosion processes (USLE). For complex sections of slopes, the method is correct only for transeuvial landscapes, while for accumulative landscapes, the mentioned connection disappears. The correlation coefficient in the humus content – magnetic susceptibility pair also decreases. This is due to the alternation of washout–accumulation zones and exits of soil-forming rocks in runoff basins, the existence of which is not provided for by the procedure for applying the USLE model of potential soil losses. The use of soil MS data has a high potential for the localisation of soil inhomogeneities associated with the differentiation of humus content and granulometric composition

Keywords: soil; magnetic properties; chernozems; organic carbon; slope

INTRODUCTION

Global climate changes and unbalanced economic use lead to the spread of a number of negative phenomena in the soil cover, one of the manifestations of which is an increase in the degree of spatial differentiation of soil values, and, consequently, the heterogeneity of agronomic properties of the soil.

Modern agricultural technologies are now increasingly striving to apply the concept of precision farming, which is an adequate response to the soil and climatic conditions of each of the individual parts of agricultural allotments. The methodological basis of this approach is the localisation of soil cover heterogeneities, which require expanding the differentiation of agrotechnological measures for a more complete implementation of potential fertility. This is especially important on sloping lands, where the additional permanent impact is caused by water erosion.

Under these conditions, there are new increased requirements for the density of the soil testing network and their frequency, which can

not always be ensured by using conventional agrochemical methods for determining soil characteristics. One consequence of this is that the list of such studies is constantly expanding, mainly due to non-contact non-destructive methods, which are characterised by high detection rates and low cost (Byndych, 2017). Among such methods, the use of applied magnetometry, in particular, the determination of soil magnetic susceptibility (MS), occupies a prominent place (Jordanova, 2016). However, the use of the method has certain geographical and technological limitations and reservations that reduce its effectiveness, first of all, this is about the origin of iron minerals in soils, differences in agrotechnical and agrochemical nature.

At the initial stage of the study on the magnetic properties of soils, work, that mainly concerned the difference in the values of the volume magnetic susceptibility of different genetic horizons of the soil profile was conducted to identify them, and pioneering work concerned

the differences between horizons A and C of the soil profile (Borgne, 1955, 1960). The informative value of pedomagnetic data turned out to be suitable for predicting the natural conditions of soil formation and the course of pedogenesis in general. The presence of highly crystallised forms of iron is accepted as an indicator (Jones and Beaver, 1964). In the future, areas related to the research on natural magnetic characteristics, mainly various types of residual magnetisation and mass-specific MS, began to develop. This is due to the high degree of association between them and soil factors used in erosion models, such as factor K in the RUSLE model (Gurka-Kostrubiec *et al.*, 2015). More diverse tasks, including determining soil contamination, were implemented using multi-frequency devices (Dearing, 1999).

The value of MS in soils depends on the content and shape of iron minerals in them, which, in turn, depend on the geography and ecology of their formation, and even on the implementation of tillage activities (Maher, 1986). The physical basis for using these methods is the state of the most magnetic compounds of the soil, these include hydroxides (lepidocrocite, ferrihydrite) and oxides (hematite, magnetite, maghemite). The share in the values of magnetic characteristics in grey forest soils and chernozems provided by the magnetite-maghemite pair is about 90%. Bulgarian researchers demonstrated that the contribution of iron carbonates (siderite) to the overall magnetism of soils is insubstantial (Jordanova, 2016). There is a constant transformation of iron minerals in the soil depending on redox conditions, and the value of magnetic characteristics changes accordingly (Menshov *et al.*, 2012). A group of Japanese researchers concluded that, thus, the current state of iron compounds corresponds to the current ecological state of the soil (Moritsuka *et al.*, 2021). It is believed that the methodological

basis for the use of MS in studies of inclined soils is its relationship with the stability of soil aggregates (Alekseeva *et al.*, 2009), the content of the clay fraction (Peluco *et al.*, 2011), and organic matter content (Wang *et al.*, 2008). Such patterns in the future will allow predicting (interpolate or extrapolate data) the numerical values of soil factors of commonly used mathematical models of erosion. For several decades, information about the magnetic properties of the soil cover has been used to solve such problems. Pedomagnetic studies provide a number of economic and technical advantages over conventional methods: increasing the productivity of measuring equipment, reducing the cost of measurements (due to automation and the use of new methods and techniques), and introducing new methods of interpolation of these reference definitions.

The purpose of the study is to identify the informative value of magnetometric methods in determining slope processes that regulate the use of certain measures to increase soil fertility and protect soils from erosion.

MATERIALS AND METHODS

Various types of magnetic susceptibility were used: volume, determined in natural occurrence, in situ (instruments: KT-5, PIMV-M, KM-7) and mass-specific, determined in laboratory conditions (instruments: KLY-2, MS2B, KLY-3) (Dearing *et al.*, 1996).

The process of determining MS through modern measuring equipment is characterised by high efficiency (the determination time for the volume MS does not exceed several seconds) and accuracy (for the mass-specific MS, the measurement error does not exceed 0.5%) of definitions, which is the main factor in its spread. The most commonly used method for determining soil MS in recent years is according to Evans & Heller (2003).

The KLY-2 Kappabridge (Czech Republic) and the Ohaus 403 laboratory scale were used to perform this study. The analysed samples, according to the mentioned Deering method, were brought to an air-dry state under normal conditions. Soil sampling was conducted from a layer of 0-20 cm. Determination of organic carbon content (followed by conversion to humus) was conducted according to DSTU ISO 14235:2005 (2007). Visualisation of the study results was performed in the QGIS programme. The Universal Soil Loss Equation (USLE) was used to determine potential soil losses.

The experimental data described in the paper were obtained on the territory of experimental sites of the Educational and Scientific Centre "Institute of Soil Science and Agrochemistry Research named after O.N. Sokolovsky", located in the northern, western, and southern parts of the Kharkiv district of the Kharkiv region. Typical medium-humus chernozems and podzolic chernozems of varying degrees of washout represent the soil cover. The plots are located on slopes of 1-5° and are used as arable land, the slope length is up to 700 m.

RESULTS AND DISCUSSION

Agronomic unevenness of the soil cover is formed due to a number of factors, including the difference in environmental conditions of soil formation (insolation isomerism, slope mode of precipitation assimilation) and the redistribution of soil substance due to the development of slope processes, primarily water erosion. That is why the objects of this study were inclined land plots. However, the existence of such irregularities is explained not only by force processes but also the action of other factors of pedogenesis. The informative value of pedomagnetic data in predicting such conditions is reported on the example of many soils in the world (Jordanova, 2016). A study by

researchers from the UK showed differences in the magnetic properties of soils in different natural and climatic zones. According to the authors, the features of the formation of pedogenic oxides are described by the ratio of pedogenic iron minerals hematite/goethite (Long *et al.*, 2011). The existence of a relationship between mass-specific MS and annual precipitation ($R = 0.81$) and average annual temperature ($R = 0.58$) was shown on the example of Serbian soils (Radaković *et al.*, 2019).

Similar results were obtained by Iranian researchers on the example of soils in the northern part of the country: the correlation coefficient between soil MS and precipitation reaches $R = 0.80$ (Pourmasoumi *et al.*, 2019). A higher bond value was obtained by Chinese researchers on feralite soils of Hainan Island – $R = 0.90$ (Long *et al.*, 2011). Moreover, there is a connection not only with the precipitation regime but also with the drainage regime (Gholamzadeh *et al.*, 2019). The relationship between soil MS and moisture was noted on the example of slope areas of the central part of the Kharkiv region (Menshov *et al.*, 2021). Complexing of magnetic indicators was used to identify megacatena soils in France (the Mediterranean coast is the foot of the Alps), complicated by the influence of low anthropogenic factors: pollution, agriculture. The advantage of using a complex of magnetic methods over the use of conventional agrochemical methods is shown (Lecoanet *et al.*, 2003).

More informative at the local level of management is the possibility of indicating the manifestation of erosion processes, when the main factor of variability in the values of agronomic characteristics of the soil are inclined processes of substance movement (Pelucco *et al.*, 2013). Thus, anomalies of humus content, granulometric composition, and soil density are formed (de Jong *et al.*, 1998). These soil characteristics have been successfully examined using

magnetometry on the example of the soils in Brazil (de Souza Bahia *et al.*, 2017) and the Czech Republic (Jakšík *et al.*, 2016). The concentration of strong magnetic iron minerals in the clay fraction of the soil (CF) also determines the relationship between the content of physical clay and MS. Thus, Brazilian researchers identified a high degree of association between MS and FG content in the slope soils of southern Brazil (Barbosa *et al.*, 2019). On the territory of Ukraine, the value of this indicator was established at

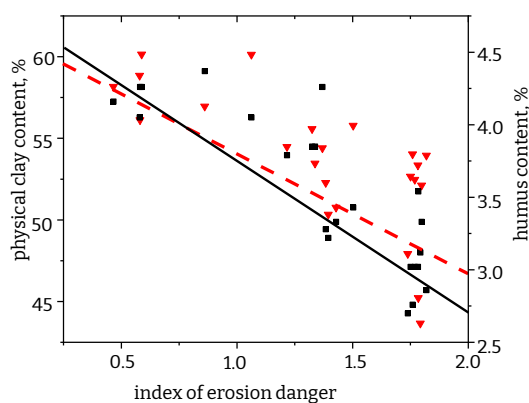


Figure 1. Graph of the dependence of the values of the erosion hazard index and the content of humus and physical clay on the example of a slope section of podzolic chernozem (Kharkiv region)

As shown in Figure 1, the calculated erosion hazard index is informative about the properties of the soil cover on slopes: there is a high degree of correlation of indicators (humus content and physical clay) and the requirements for homoscedasticity of the sample are met. A similar trend is also typical for the use of magnetometric methods instead of erosion modeling.

These results were obtained on a gentle slope, without complications. As the degree of terrain differentiation increases, dependencies arise that are not explained in simple models. Such results include detailed statistical studies

$R^2 = 0.83$ for podzolic chernozems in the north of the Kharkiv region (Menshov *et al.*, 2018).

Modern models of erosion are one of the means of parameterisation of slope processes, they give a fairly clear idea of the redistribution of soil matter, including its organic part. Such studies on the example of a site of podzolic chernozem showed a high degree of association – coefficients of correlation with MS are more than 0.9 (Menshov *et al.*, 2018). An example of such a connection is shown in the graphs of Fig. 1 and 2.

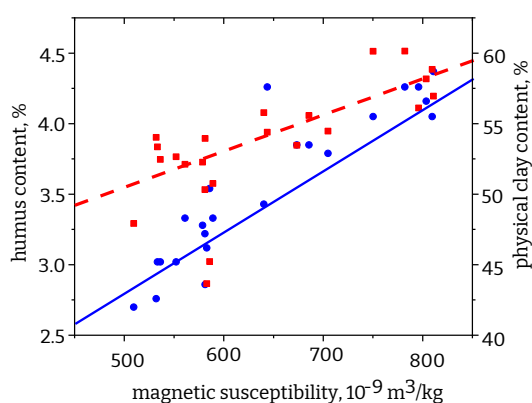


Figure 2. Graph of the dependence of the values of the mass-specific magnetic susceptibility of soil and the content of humus and physical clay on the example of a slope section of podzolic chernozem (Kharkiv region)

that showed a low level of reliability of the results and correlations obtained (Kruglov *et al.*, 2018). A similar trend was observed by Chinese researchers (Liu *et al.*, 2015). Therefore, the logical step is to expand research using a differential approach.

It is shown that in different sections of the complicated slope, the degree of relation between the values of MS, potential flushing, and humus content decreases. Thus, the almost complete absence of such a connection in the eluvial parts of the agricultural landscape is proved, while in the transeluvial areas, it is reliable. In the

range of values of the topographic coefficient LS of the USLE model 0...0.30, the correlation coefficient p between the humus content and soil MS

is 0.25, in the range 0.26...0.99, respectively, 0.82, and close to 0 in accumulative elements (Fig. 3). The total for the sample is $p = 0.49$.



Figure 3. Features of the spatial distribution of Corg content (A) and values of the topographic factor LSK of the USLE model (B)

Figure 3 shows the case when the humus content in the soil in general increases with increasing values of potential erosion, but there are substantial deviations in the central and north-eastern parts of the site, which explains the relatively low value of the correlation coefficient between them. MS of the soil here has a high degree of association with the humus content ($p = 0.63$). Figure 4 clearly shows a decrease in MS in the northern part of the field – this corresponds to the territory of the basin with washed-out soils, and, accordingly, with low values of humus content (Fig. 3 A). The maximum MS values are located in the centre of the field and correspond to one of the humus content maxima.

The low level of correlation between topographic indicators and humus content is associated with the existence of numerous washout-accumulation zones, the existence of which is

not provided for by the procedure for applying the USLE model of potential soil losses. Additional complications, such as a developed network of runoff basins or a large proportion of non-eroded land, reduce the level of this connection, which partially echoes the results of Brazilian researchers (Barbosa *et al.*, 2019).

High values of the MS correlation coefficient and humus content were also shown on the example of slope areas of chernozem soils in the southern part of the Kharkiv region. In this study, Spearman's p between the humus – MS content is in the range of 0.75-0.81 and depends on the frequency of MS determination (Kruglov *et al.*, 2021). This is also confirmed by the results of an international team of specialists who showed the patterns of transformation of pedogenic magnetite under the influence of the main factors of the current stage of pedogenesis

(Lyons *et al.*, 2010; Maxbauer *et al.*, 2017; Ramos *et al.* 2017). The magnetic parameters of the soil have even been proposed to be used as one of the criteria for its conservation (Quijano *et al.*, 2014) and determination of the degree of its degradation (Sadiki *et al.*, 2009).

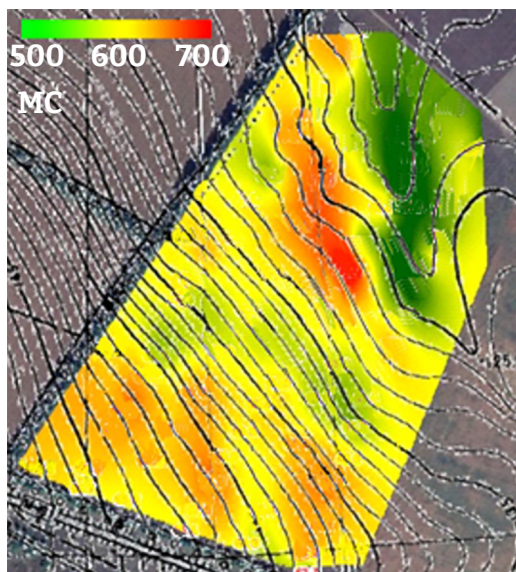


Figure 4. Cartogram of the mass-specific magnetic susceptibility of the soil of the experimental site

Thus, a high level of the information content of pedomagnetic data for transeleuvial areas of the agricultural landscape, i.e. inclined areas can be stated. The obtained correlation coefficients between the MS of inclined soils and the values of mathematical modelling of erosion are close to the values obtained on the example of USLE and WEPP. This allows stating the prospects of research considering options for replacing the most resource-intensive methods of agrophysics and agrochemistry with magnetic exploration methods, in particular, the determination of MS (Jimenez *et al.*, 2017)

The use of the method in accumulative areas is difficult, this is not provided for in the most

common versions of the USLE. (Santos, 2013). The correlation coefficient between the examined indicators is low here (0.1..0.3), which was also noted on the example of various landscapes in Brazil.

CONCLUSIONS

The application of data on the magnetic susceptibility of soils has a high potential for localisation of inhomogeneities of the values of agronomic indicators associated with the differentiation of the humus content of granulometric composition, and, accordingly, some other related fertility indicators, which is especially important in the implementation of precision farming technologies. This method of assessing the agricultural landscape has an order of substantially lower cost and labour intensity indicators compared to using any agrophysical or agrochemical method with a similar configuration of the soil characteristics testing network.

This application is based on a high degree of correlation between the values of the mass-specific magnetic susceptibility of the soil and the content of organic matter (humus), physical clay (0.01 mm particles) and the results of mathematical modelling of erosion processes. On the example of chernozem soils of the Kharkiv region, high correlation values are shown, both between the mass-specific magnetic susceptibility and organic carbon content, and the values of the topographic factor (LS) of the USLE.

However, the use of magnetometry methods for the needs of agronomic soil science and in agronomic practice faces a number of methodological problems, including methods and methods of conducting field measurements, and the reliability of the results obtained. In particular, the method shows unsatisfactory results in areas with complicated terrain with alternating washout-accumulation zones and existing active foci of linear erosion. There is also a low level of correlation between the values of magnetic

susceptibility and humus content in eluvial landscapes with low values of the topographic factor of the USLE model, and non-eroded soils are developed in such landscapes. The method demonstrates the highest efficiency in uncomplicated agricultural landscapes (with a flat slope without runoff basins) and in transeluvial (slope) areas with a pronounced effect of erosion processes. More promising is the integration of pedomagnetic methods with the

results of applying more modern mathematical models of erosion, considering the existence of washout-alluvial zones and foci of accelerated water erosion.

None.

None.

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CONFLICT OF INTERESTS

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Магнітна сприйнятливість схилових ґрунтів та її зв'язок з деякими агрономічними показниками

Анотація. Сучасний аграрний комплекс вимагає застосування нових методів визначення характеристик ґрунтів для адекватного інформаційного забезпечення новітніх технологій, що часто неможливо забезпечити за допомогою традиційних методів. Мета роботи – розкрити інформативність магнітометричних методів при визначенні схилових процесів, що регламентують застосування тих чи інших заходів з підвищення родючості ґрунтового покриву та охорони ґрунтів від ерозії. Дослідження проведено на схилових агроландшафтах Харківської області. При виконанні даного дослідження для визначення магнітної сприйнятливості використовувався каппамісток KLY-2 (Чехія) та лабораторні ваги Ohaus 403. Відібрані проби ґрунту, відповідно до прийнятих методик, було доведено за нормальних умов до повітряно-сухого стану. Відбір проб ґрунту проводився з шару 0-20 см. Візуалізація результатів дослідження та визначення потенційних втрат ґрунту (модель USLE) проводилась у програмі QGIS. Було проаналізовано кореляційний зв'язок магнітної сприйнятливості на простих та ускладнених схилах. Встановлено, що на простих схилах значення магнітної сприйнятливості ґрунту має високе значення цього показника з вмістом фізичної глини та органічного вуглецю. Водночас відзначається високий ступінь зв'язку цього показника з результатами математичного моделювання ерозійних процесів (USLE). На ускладнених ділянках схилів метод коректний лише на транселювіальних ландшафтах, тоді як для акумулятивних ландшафтах згаданий зв'язок зникає. Знижується і коефіцієнт

кореляції у парі уміст гумусу – магнітна сприйнятливість. Це пов'язане з чергуванням зон змиву-намиву та виходами ґрунотворчих порід в улоговинах стоку, існування яких не передбачено процедурою застосування моделі потенційних втрат ґрунту USLE. Застосування даних про МС ґрунтів має високий потенціал при локалізації ґрунтових неоднорідностей, пов'язаних з диференціацією вмісту гумусу та гранулометричного складу

Ключові слова: ґрунтовий покрив; магнітні властивості; чорноземи; органічний вуглець; схили

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Invasive plant species and their threat to biodiversity

Abstract. The problem of the uncontrolled spread of alien plant species matured in the world in the second half of the 20th century, and in recent decades it has become the main threat to the biological diversity of various regions of the world. Prevention of biological Invasions is a new urgent task

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in the field of nature protection, which determines the relevance of the study. The purpose of the study is to determine and predict the distribution area of invasive plants, based on the use of the following methods: comparative morphological-ecological-geographical, route using determinants and atlases of plants of Ukraine, and the method of structural analysis. It is established that the characteristic features of invasive plant species are very high tolerance to habitat and climatic conditions, high rate of reproduction, simple and effective distribution by wind, water, animals, and rapid growth, which contributes to the displacement of slow-growing plants of other species and uncontrolled spread in the absence of natural enemies and restrictions. A particular danger to the biodiversity of Ukraine is the spread of invasive plant species: Sosnowsky's Hogweed (*Heracleum sosnowskyi*), Canadian Goldenrod (*Solidago canadensis* L.), American maple (*Acer negundo* L.), Red Oak (*Quercus rubra*), Common Ragweed (*Ambrosia artemisiifolia* L.), Common Milkweed (*Asclepias syriaca* L.), Silver Berry (*Elaeagnus angustifolia*), American pokeweed (*Phytolacca Americana*), Ecballium (*Ecballium elaterium*), Common Sandbur (*Cenchrus pauciflorus* Benth), Wall Barley (*Hordeum murinum* L.), Jerusalem Artichoke (*Helianthus tuberosus*), etc. The results of the study are an important scientific and practical basis for developing national and regional strategies for controlling invasive plant species

Keywords: weed plants; appearance; distribution area; harmfulness; control methods

INTRODUCTION

Invasive plant species spread naturally or through human intervention and pose a threat to the flora and fauna of the local ecosystem. This can lead to the extinction of native species, which is a particular problem. In addition to environmental impacts, invasive plant species also cause economic damage in crop cultivation, forestry, and other industries that depend on biodiversity and ecosystem services. In particular, invasive plant species can reduce yields, worsen soil quality, reduce the potential for ecotourism, etc. The economic damage in the European Union from invasive plant species reaches 12 billion euros per year (Reges *et al.*, 2018; Shuvar *et al.*, 2021).

Based on the results of extensive research by a number of authors, for practical reasons, such alien species were also included in invasive species, the introduction and/or spread of which is a threat to the economy and/or human health. Invasive species have a negative impact on the environment, due to the transformation of natural habitats and the displacement of native species

in the process of competition or depletion of the nutrient medium (Bhowmik, 2014; Ivashko, 2019; Shuvar *et al.*, 2019)

Such researchers as A. Bang, F. Verloove, B. Bharat *et al.* argue that almost all over the world, invasive alien plant species have been introduced to local communities as a result of agricultural or horticultural activities. Among them are previously cultivated species (agricultural, vegetable, medicinal, ornamental plants) or accidentally introduced other taxa. Researchers estimate that in Europe, almost 80% of invasive species were introduced in this way (Bharat *et al.*, 2014; Verloove *et al.*, 2021; Bang *et al.*, 2022).

Alien plant species are able to adapt more easily and quickly in unstable phytocenoses with a disturbed natural structure and mechanisms of their functioning. This agroecosystem group, as habitats under constant pressure and strongly altered by humans, is most susceptible to invasion by other atypical plants. In addition to arable land, they include meadows, perennial plant-

ings, vacant lots and fallows, and adjacent territories (trees and shrubs in the field, roads and roadways, and territories around residential and outbuildings). These areas become habitats for plants of foreign origin, because natural habitats with little human intervention are more difficult to control, and the process of introducing invasive plants can take hundreds of years (Tiwari *et al.*, 2014; Rashid *et al.*, 2021; Sharma *et al.*, 2022).

According to researchers, in particular, V.V. Protopopova *et al.* (2003), out of almost 3,500 plant species, about 30% are species of foreign origin (Protopopova *et al.*, 2003). However, only a few of them threaten nature in modern conditions and can be classified as invasive alien species (Lastrucci *et al.*, 2019, Khoury *et al.*, 2019; Kumar *et al.*, 2020).

Thus, most studies are devoted to the biology of invasive species and the ecology of their distribution. However, few studies have identified methods of preventing such invasions. Therefore, timely and effective counteraction to biological invasions is important in the field of nature protection and biodiversity conservation and determines the relevance of the study.

The purpose of the study is to identify and predict the spread of invasive plants.

MATERIALS AND METHODS

The study was conducted during 2010–2022 in accordance with existing methods, collected herbariums and an analytical review of literature sources on individual taxa, their morphological, ecological, and other features. The object of research is species of invasive plants in the composition of natural, semi-natural, anthropogenic flora complexes and plant communities of vegetation cover.

When investigating the species diversity of flora complexes, a comparative morphological-ecological-geographical method was used. The species composition of invasive plants was

determined by the route method using determinants and atlases of plants of Ukraine. The obtained information about plant species is reduced to taxonomic (The Plant List..., n.d.) and syntaxonomic correspondence. A group of invasive plants was examined using classical methods of structural analysis.

The studies covered the main areas of invasive vegetation growth: residential areas, ruderal areas, park and forest-park zones, lawns, arable land, and degrading natural ecotopes in the western Forest-Steppe of Ukraine.

The study was conducted in accordance with ethical requirements. Experimental plant studies, including the collection of plant material, were in accordance with institutional and international guidelines. The study also followed the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1963).

The climate of the area of the study zone is characterised as temperate continental (Fig. 1).



Figure 1. Geographical location of the research area

Note: on the map – the research area is the western Forest-Steppe of Ukraine

In addition, in the course of the study, to achieve this goal, practical recommendations, scientific and methodological provisions were used to determine possible ways of spreading and

controlling invasive plant species. In addition, the theoretical segment of the study includes papers of researchers in the field of herbology, and the information components of the study were official materials and publications, in particular: the Strategy for the Biodiversity Protection (European Union) and the Strategy for Biosafety and Biological Protection for 2022-2025 (Ukraine).

Monographic and periodical literature was also used, including the results of the authors' findings. A comparison method was used to process the materials and an abstract-logical method aimed at investigating the causes of the spread of invasive plant species.

In the course of the study, a complex of special and general scientific groups of methods was used, namely: induction and deduction (for a more complete analysis and study of factors contributing to the development of invasive plant species, namely induction was used to obtain data, and deduction – to create general principles based on these data), dialectical (to clarify the patterns of modern causes of the spread of invasive species), analysis (to analyse the collected information, draw conclusions, provide recommendations, determine the prospects for further research), statistical methods (for quantitative identification of the obtained data), synthesis (to combine the acquired knowledge in a single whole), and comparative analysis (for compiling the results obtained).

The study of the possible spread of invasive plant species and the development of a forecast model was conducted for the following species: Sosnowsky's hogweed (*Heracleum sosnowskyi*), Canadian goldenrod (*Solidago canadensis* L), Common Milkweed (*Asclepias syriaca* L.) American pokeweed (*Phytolacca Americana*). Using the Python programme, a model was developed that characterises the state and intensity of the increase in the number of these species for the period up to 2050.

RESULTS AND DISCUSSION

Assessment of the nature of the spread of adventitious plants in Ukraine as dangerous for natural development and optimal functioning of regional flora gives grounds to consider it appropriate to take a comprehensive and global approach to solving the problem of phyto-invasions. Ultimately, it should be considered as one of the priority areas of research and the effectiveness of environmental organisations. It is in this aspect that research continues in institutions of higher education that provide monitoring and control of adventitious weeds of agroecosystems, since preventing the negative impact of adventitious plants on biodiversity at different levels (species, cenotic, ecosystem) is the basis for establishing the diversity of invasive species and slowing/stopping the biological invasion of alien plants.

Studies conducted by experts from different countries have shown that adventitious plants pose a threat mainly to stenotopic species, changing the ecotopes in which they grow, causing insularisation of their populations and, as a result, genetic, taxonomic, and cenotic depletion of natural vegetation cover. The migration of plants, especially invasive species, leads to certain shifts in the balance of ecosystems. These changes (population suppression or decline) with negative consequences occur at all levels (Blicharska *et al.*, 2019; Lyytimäki *et al.*, 2020; Zhou *et al.*, 2022; Dorber *et al.*, 2023).

The protection of agricultural biodiversity has recently become an important challenge for countries around the world, including Ukraine. On the one hand, measures are aimed at protecting rare plant and animal species, and valuable natural habitats, and on the other hand, more and more attention is paid to the protection of biocenoses as an integral functional ecosystem. The source of threats to biological diversity is the introduction of alien plant species that show the

ability to constantly and spontaneously populate, develop, and modify plant communities.

It is established that alien species entered and still enter the territory of Ukraine deliberately to increase agricultural and forest production, market competitiveness, and pest control. Numerous species of them have been used and are still being used as ornamental plants, while the search for new forms for introduction into the culture or natural flora continues.

In modern conditions, the biggest problem for certain plant species is the climate, so some plants die, unable to withstand long periods of drought or harsh winters. However, those plants that come from areas with similar climatic conditions quickly adapt to new conditions and even conquer new territories. The mainstay at the first stages of settlement is usually ruderal places of stay – areas of ports, railway stations, and places of cargo transshipment. However, new plant species migrate (carried by wind, water, etc.) and get to another substrate and begin the next stage of territory capture. Those of the plants that settle on a native alien range are the most expansive – they produce viable offspring, often in large numbers, settle over long distances from the mother plants and colonise large territories in a short time

Among the methods of spreading invasive plants, the following are distinguished:

- n clogged seeds, feed grain, hay, straw, mulch, irrigation water, manure, peat compost, manure;

- n completely uncontrolled penetration of various invasive forms of weeds into the territory of Ukraine;

- n movement of contaminated equipment and vehicles in clean areas;

- n animal husbandry and wildlife;

- n construction/repair of communication routes using weed-infested material; recreation;

- n water and wind transfers (natural disasters, hurricanes, dust storms, floods).

- n freight rail and road transport.

Among the plants in Ukraine, according to various estimates, there are from 600 to 800 alien species, which consists of 14% of the plant world, of these, about 50 species are dangerously invasive (Shuvar *et al.*, 2021, Protopopova *et al.*, 2003).

Three stages of settlement of new territories by invasive species have been established: 1) Introduction – consists of the transfer of material for reproduction of a certain species outside the current area of its distribution and ends with the formation of an adult population; 2) colonisation – during which the initial population reaches the level of self-reproduction and expansion of the area of its existence; 3) placement/capture of territory and penetration into natural groups.

As a result of the study, a database of invasive plant species established in agricultural areas and ruderal cenoses on the territory of the western forest-steppe of Ukraine was created (Table 1).

Table 1. List of invasive and potentially invasive plant species identified in the western Forest-Steppe of Ukraine (2010-2022)

Species name	Origin	Life form	Hygroform
<i>Asclepias syriaca L.</i>	North American	Perennial	Xero-mesophyte
<i>Heracleum sosnowskyi</i>	Caucasian	Biennial Perennial	Mesophyte
<i>Solidago canadensis</i>	North American	Perennial	Xero-mesophyte
<i>Heracleum mantegazzianum</i>	Caucasian	Biennial, Perennial	Mesophyte

Table 1, Continued

Species name	Origin	Life form	Hygroform
<i>Ambrosia artemisiifolia</i> L.	North American	Annual	Xero-mesophyte
<i>Bidens frondosa</i>	North American	Annual	Xero-mesophyte
<i>Xanthium albinum</i> (Widd.) H. Scholz	Avg. European	Annual	Xero-mesophyte
<i>Conyza canadensis</i>	North American	Annual	Mesoxerophyte
<i>Echinocystis lobata</i>	North American	Annual	Mesophyte
<i>Helianthus tuberosus</i>	North American	Perennial	Xeromesophyte
<i>Hordeum murinum</i> L.	North African	Annual	Mesophyte
<i>Impatiens glandulifera</i>	East Asian	Annual	Mesophyte
<i>Impatiens parviflora</i>	Central Asian	Annual	Mesophyte
<i>Lepidotheca suaveolens</i>	North American	Annual	Mesophyte
<i>Lupinus polyphyllus</i>	North American	Biennial Perennial	Mesophyte
<i>Oenothera rubricaulis</i>	North American	Biennial	Mesoxerophyte
<i>Phalacrolooma annuum</i>	North American	Annual	Mesophyte
<i>Phytolacca americanae</i>	North American	Perennial	Mesophyte
<i>Vicia villosa</i>	Mediterranean	Annual	Xero-mesophyte
<i>Xanthoxalis dillenii</i>	North American	Perennial	Xero-mesophyte

Source: European Commission, Directorate-General for Environment (2002)

Predicting the rate of spread of invasive plant species depends on many factors, such as climatic conditions, soil type, the presence of natural enemies, and human activity. The developed predictive models use various approaches, such as mathematical models, statistical methods, or geographic information systems. Predictive models can help identify potential risk areas for the spread of invasive species and develop effective measures to control and manage them. However, it is important to note that predictive models cannot predict all possible scenarios for the development of invasive species, so continuous monitoring and analysis of data is key to effective control of them.

In the completed study, the study of the possible spread of invasive plant species and the development of a forecast model was conducted for Sosnowsky's hogweed (*Heraclium sosnowskyi*), the Canadian goldenrod (*Solidago canadensis* L), Common Milkweed (*Asclepias*

syriaca L.), and American pokeweed (*Phytolacca Americana*). Considering the rate of spread of these species and their prevalence among other biological groups of weeds, the Python study developed a model that characterises the state and intensity of the increase in the number of these species for the period up to 2050 (Fig. 2).

Thus, it is established that invasive plant species, if no measures are taken to control them, can spread quite quickly, and in the period until 2050, the number of such plants will be more than twice their current number. The developed predictive model indicates the rate of spread of invasive plant species and serves as a scientific basis for developing specific effective measures to control their abundance. The spread of invasive plant species creates a problem for diversity in different countries of the world. Therefore, the EU countries have developed and approved a strategy for the protection of biodiversity, covering 6 priority tasks (Osipenko, 2020).

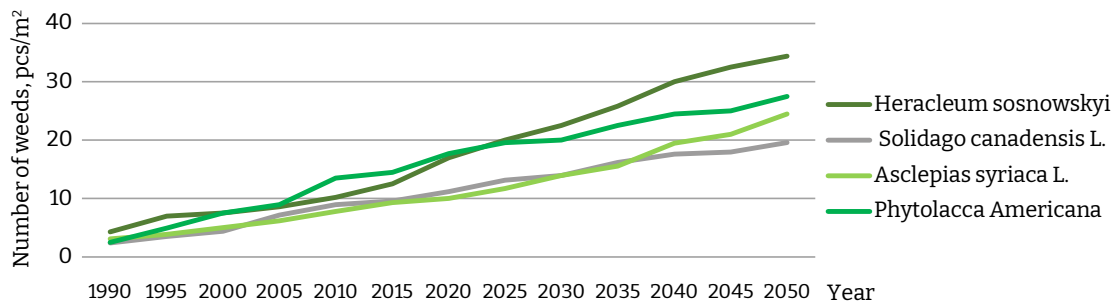


Figure 2. Forecasting the spread of *Heracleum sosnowskyi*, *Solidago canadensis* L., *Asclepias syriaca* L. and *Phytolacca Americana*

1. Protection and restoration of the natural state;
2. Maintaining and improving ecosystems and their functions;
3. Ensuring sustainable development of agriculture and forestry;
4. Ensuring sustainable use of fish resources;
5. Control of invasive alien species;
6. Overcoming the global biodiversity crisis.

According to researchers' estimates 80% of invasive foreign plants were imported to Ukraine as ornamental or agricultural plants. An example is Japanese Larch (planted in forests as an ornamental, creating hybrids with native European larch), Sosnowsky's hogweed (potentially forage plant), alfalfa (legume forage plant, for green manure), etc. (Najberek *et al.*, 2022, Reges *et al.*, 2018).

Invasive species threaten the flora of a particular area by competing with local taxa for an ecological niche, which can lead to complete habitat control in new areas due to basic traits, including:

- n very high tolerance to the habitat and climatic conditions;
- n high activity of generative or vegetative reproduction and reproduction during the growing season and long viability of seedlings;
- n rapid seedling growth, early maturity for reproduction, and relatively short life cycle;

- n easy and efficient distribution by wind, water, or animals;

- n anthropogenic intervention and various logistics routes within the state and from abroad;

- n ability to cross with other species, create polyploids and ecotypes;

- n rapid growth, which leads to silencing and complete displacement of weaker plants of other species;

- n rampant spread in the absence of natural restrictions and enemies.

The characteristic features of invasive plants are also indicated by M. Dumitrașcu, I. Grigorescu, G. Kuscicsa, M. Doroftei, M. Năstase, C. Dragotă, T.S. Dvirna, claiming that they include: rapid growth and reproduction, ability to occupy uncultivated land, short development cycle, early flowering and self-seeding, generation of large numbers of fruits and/or seeds, efficient reproduction, ability to use local pollinators, excellent phenology from native species helps them compete effectively, resistance to disease and pest damage (Dumitrașcu *et al.*, 2014).

As for the causes of plant invasiveness, Z. Paukova, V. Kaderova, L. Bakay, K.O. Reinhart, A. Packer, V.D. Putten, I.A. Shuvar note that the movement and spread of alien species in a new environment are facilitated by the absence of natural enemies and other restrictions in their natural environment. Pollution of the surrounding

habitat and human destruction of natural habitats of native species are also substantial factors. A particularly serious threat is progressive climate change, in which alien species are more likely to settle in new areas where it is more difficult for native species to survive (Reinhart *et al.*, 2003; Paukova *et al.*, 2013; Shuvar *et al.*, 2021).

According to C. Brickell, G. Stohlgren, D.T. Barnett, J.T. Kartesz, a number of factors contribute to the spread of invasive plants. Thus, most often plants are spread by seeds, through the wind (anemochoria), water (hydrochoria), and animals (zoochoria). Distribution is also possible when plant residues are accidentally or intentionally dumped into sewers, ponds, forests, compost, etc. (Brickell *et al.*, 2016, Stohlgren *et al.*, 2003).

The sources of invasive plant species and the causes of their spread were examined by a number of researchers: J. Andreu, P. Hulme, I. Shuvar, H. Korpita, etc. Thus, the authors established that introduction, natural mechanisms of distribution, climate change, and anthropogenic factors most affect the spread of invasive species, which correlates with the study performed (Hulme *et al.*, 2008; Andre *et al.*, 2019; Shuvar & Korpita, 2021).

Invasive alien species are often established in all types of habitats. They were accidentally introduced to the local flora or imported as cultivated, ornamental, or medicinal species. Among agricultural land, in addition to arable land, there are also areas that are not used for agriculture (fallow, field roadsides, roads, drainage ditches, etc.), which are often a place of growth of invasive plants. Such habitat environments, which are located in the field of human activity, are more easily captured by aggressor plants than by natural plant grouping. Under favourable conditions, invasive plants can enter adjacent ecosystems from them. The authors' studies show that extensive agricultural ecosystems (ecological, with simplified tillage or cultivation of perennials for energy needs) are more at risk of

penetration of invasive segetal plants than ecosystems that are subjected to constant anthropogenic pressure due to intensive plant cultivation (crop cultivation technology, plough tillage).

Action programmes on invasive plant species as a threat to biodiversity, which are confirmed in the conducted study, were considered in their papers by S.M. Haq, P.E. Hulme. Among the measures to prevent the spread of invasive plants, the following deserve special attention:

- n vehicles and equipment must be free of invasive plants and seeds;
- n minimising ground disturbance during all construction and maintenance work;
- n promoting the creation of a healthy plant community;
- n limiting the movement of soil or gravel clogged with weeds;
- n using certified seed mixes that are weed-free;
- n elimination of locations – the neutralisation of existing invasive plant groups and control of new ones;
- n maintenance and restriction of the movement of invasive plants from neighbouring land or administrative territories;
- n highways, railways, and waterways are often corridors that need to be monitored to limit the spread of invasive plants.;
- n protection of areas that are clean from invasive plants;
- n providing information to the general public about the limited distribution of weeds;
- n production, distribution among various segments of the population and placement of informative materials for familiarisation (tables, posters, information leaflets, etc.);
- n keeping machinery and vehicles clean (Hulme *et al.*, 2008; Haq *et al.*, 2021).

According to R. Dean, invasive plant species are able to quickly adapt to new environments and cover large areas. They can also have a major

impact on biodiversity and ecosystem functioning and can change the structure and composition of soils, disrupt interactions with animals and other plants, and affect energy and material flows in the ecosystem, which is also confirmed in the conducted study (Dean *et al.*, 2016).

Another confirmation of the study is that invasive plant species can be carriers of diseases and pests, which can cause even more damage to local ecosystems and the economy (Heshmati, 2019).

In his study, the author argues that invasive plant species can be effective tools for solving soil erosion problems and restoring degraded ecosystems. However, their potential impact on local ecosystems and other risks should be carefully examined before use (Jamil *et al.*, 2022). In addition, the conducted study correlates with the opinion of leading researchers, in particular, C.K. Peres *et al.* (2018) that an invasive alien species is a descendant species from another ecosystem whose introduction and/or spread threatens local biodiversity.

The results of this study are confirmed in the studies of a number of authors – K. Najberek, A. Olszańska, B. Tokarska-Guzik, K. Mazurska, Z. Dajdok, W. Solarz, L. Lastrucci, G. Fiorini, L. Lunardi, D. Viciani, who believe that it is necessary to develop comprehensive methods for localising, controlling and preventing the spread of invasive plant species (Lastrucci *et al.*, 2019; Najberek *et al.*, 2022). In his papers, V. Manral, together with his co-authors, highlights various action programmes for invasive plant species that are confirmed in practical implementation. Among them, the following can be distinguished: control and monitoring, physical destruction, biological control, chemical control, the use of agrotechnical means (cover crops, mulching, and composting), and legislative control (Manral *et al.*, 2020).

I. Rashid notes that the introduction of environmental education and raising public awareness about the negative impact of invasive

species on local ecosystems can be an effective measure to prevent their spread and reduce the harmful impact on biodiversity. It is also important to develop and implement management strategies for invasive species that regulate their distribution and effectively use resources to control them. Special attention should be paid to preventing the spread of invasive species through international trade in plants and seeds. Quality control and compliance with international standards for plant exports and imports can substantially reduce the risks of spreading invasive species from one territory to another, which is also highlighted in the study (Rashid *et al.*, 2021).

Notably, the decree of the Cabinet of Ministers of Ukraine No. 573 “On approval of the action plan for the implementation of the biosafety and biological protection strategy for 2022-2025” (2022, July) came into force in Ukraine. The implementation of this strategy is aimed at ensuring human safety and preserving biological diversity in Ukraine. The action plan provides for a number of actions to prevent and control the spread of invasive plant species, including the creation of a database on invasive species, the development of action plans to reduce and control them, and the raising of public awareness about the problem of the spread of invasive species. These measures can contribute to the conservation of biological diversity in Ukraine and reduce the negative impact of invasive species on ecosystems.

CONCLUSIONS

Unlimited movement of people, goods, and services contributes to the spread of invasive species, the sources of which are most often: seeds, vegetable seedlings imported from abroad, and ornamental plants grown in containers. In addition to the ill-conceived and destructive destruction of ecosystems by humans, species invasions pose the greatest threat to natural biodiversity.

Invasive species negatively affect the native components of plant communities. In extreme cases, they can lead to a complete destruction of the natural ecological balance of habitats. They cause substantial economic damage to the global economy. It is necessary to assess the risk before introducing new species to cultivation to reduce the impact of this negative process.

Measures aimed at limiting the emergence and prevention of colonisation by invasive species, which include methods aimed at reducing the area occupied by foreign species (for example, regular mowing or spot destruction of plants in the initial phase of colonisation) are also important, which contribute to reducing seed production and germination due to mechanical removal of inflorescences and harvesting of plants before seed maturity.

It is important to reduce the area of land that can be a potential habitat for invasive species (for example, areas with a disturbed ecological structure, and devastated and abandoned land). Deliberately spreading invasive species and using them in large-scale public plantings should be avoided, considering that many problematic taxa were introduced to botanical gardens as ornamental plants.

Training of advisory personnel and training of farmers will substantially affect the restriction of the distribution area of this group of plants, which are a real threat to the biodiversity of agro-phytocenoses and the environment in general.

It is considered appropriate to develop a comprehensive programme for investigating invasive processes in natural and cultural phytocenoses of Ukraine, aimed at implementing a set of priority scientific research to reduce the threat of invasive plants, in particular:

- a) introduction and maintenance of a register of invasive plant species with the determination of the degree of threat to individual regions;
- b) creation of a system for monitoring inva-

sive plant species in forests, meadows, and other types of phytocenoses to determine the rate of invasion and distribution area of individual species;

c) development of a strategy to prevent, manage, and reduce the risks associated with invasive plant species in agriculture and forestry in the context of global climate change;

d) elucidation of the economic, social, and environmental consequences of the expansion of invasive plant species;

e) strengthening coordination and information exchange between researchers (in Ukraine and internationally) by users of natural plant resources and regulatory authorities on integrated approaches to managing and preventing invasive processes.

It is particularly important to increase the involvement of ecosystem users in training to ensure early detection and control of the number of invasive plants within a certain distribution area. In addition, such measures will increase scientific understanding of the mechanisms of the spread of invasive species and ensure the effectiveness of control measures.

The scientific originality of the study is that for the first time in the territory of the western Forest-Steppe of Ukraine, taxonomic observation of the detection and spread of invasive plants was performed to develop predictive models of their behaviour and methods for controlling the number and distribution area.

The prospect of further research is to examine the mechanisms and factors that influence the spread and increase of populations of invasive plant species, develop effective strategies for their control and management.

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CONFLICT OF INTERESTS

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Інвазійні види рослин та їх загроза біорізноманіттю

Анотація. Проблема неконтрольованого поширення чужорідних видів рослин назріла у світі в другій половині ХХ століття, а в останні десятиліття стала головною загрозою біологічному різноманіттю різних регіонів світу. Запобігання біологічним інвазіям є новим актуальним завданням у сфері охорони природи, що зумовлює актуальність дослідження. Мета дослідження – визначити та спрогнозувати ареал поширення інвазійних рослин на основі використання методів: порівняльного морфолого-еколого-географічного, маршрутного з використанням визначників та атласів рослин України та методу структурного аналізу. Встановлено, що характерними особливостями інвазійних видів рослин є дуже висока толерантність до середовища існування та кліматичних умов, висока швидкість розмноження, просте та ефективне поширення вітром, водою, тваринами та швидкий ріст, що сприяє витісненню повільно зростаючих рослин інших видів і неконтрольоване поширення за відсутності природних ворогів і обмежень. Особливу небезпеку для біорізноманіття України становить поширення інвазійних видів рослин: борщівник Сосновського (*Heraclium sosnowskyi*), золотарник канадський (*Solidago canadensis* L), клен американський (*Acer*

negundo L.), дуб червоний (*Quercus brabra*), амброзія звичайна (Амброзія полинолиста (*Ambrosia artemisiifolia* L.), молочай звичайний (*Asclepias syriaca* L.), срібляста ягода (*Elaeagnus angustifolia*), американська польова трава (*Phytolacca Americana*), екбалліум (*Ecballium elaterium*), піщаниця звичайна (*Cenchrus pauciflorus Benth*), ячмінь стінний (*Hordeum murinum* L.), топінамбур (*Helianthus tuberosus*) та ін. Результати дослідження є важливою науково-практичною основою для розробки національних та регіональних стратегій боротьби з інвазійними видами рослин

Ключові слова: бур'янисті рослини; зовнішній вигляд; зона розподілу; шкідливість; методи контролю

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Symbiotic productivity of soybeans depending on inoculation and fertiliser in conditions of the Right-Bank Forest-Steppe

Abstract. Given the high value of the biochemical composition of soybean seeds and the versatility of using this crop, the need for it will continue to grow, which makes it necessary to improve existing and develop new technologies for its cultivation, considering local agroclimatic resources. Therefore, this study, aiming to investigate the agroecological foundations of the use of chemical and biological techniques in modern technologies for growing soybeans, is relevant. The purpose of the study was to identify the features of the formation of symbiotic productivity of soybeans under the influence of bacterial and mineral fertiliser in the conditions of the Right-Bank Forest-Steppe of Ukraine. A field method was laid down according to the developed scheme to achieve this goal. The positive effect of mineral fertiliser and inoculation on the formation of the symbiotic apparatus of soy and its productivity was established. The smallest increase in the number of root nodules was noted for the introduction of $N_{45}P_{60}K_{60}$ – 24.7-27.3%, depending on the variety. Small initial doses of nitrogen were more effective – within the limits of N_{15-30} – they provided an increase in the number of active

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bulbs by 51.2-106.9%. Bacterisation of seeds with the complex bacterial preparation Phosphonitragine increased the number of active nodules on soybean roots by 106.8-138.6%, depending on the variety. The interaction of technological methods of mineral fertilisation and inoculation contributed to an increase in both the number of nodules with leghemoglobin – by 128.5-198.6%, and their mass – by 111.1-147.6%. The soy symbiotic apparatus was maximally developed by interacting seed inoculation factors with a bacterial preparation containing *Br. japonicum* and *B. Mucilaginosus* strains and applying $N_{30}P_{60}K_{60} + N_{15}$ in the budding phase. This technological model of crop cultivation provided the highest productivity of legume-rhizobial symbiosis of soybean plants in terms of the volume of accumulation of symbiotically fixed nitrogen – in the early-ripening soybean variety Vilshanka – 124.2 kg/ha, in the medium-ripening variety Suziriia – 130.3 kg/ha. The practical importance of the obtained results is in the improvement of varietal technologies for growing soybeans based on the complex application of seed inoculation with a bacterial preparation and the introduction of nitrogen fertilisers in retail against the background of phosphorus-potassium fertiliser

Keywords: mineral fertiliser; variety; symbiotic apparatus; active symbiotic potential; biological nitrogen

INTRODUCTION

Soy (*Glycine max*) occupies a leading place in world agriculture as a crop that can be harvested twice (protein and oil) in one growing year, is characterised by a unique biochemical composition of seeds, the versatility of use, high production growth rates, a positive effect on the qualitative composition of the soil and the ability to fix atmospheric nitrogen in interaction with nodule bacteria. Given the substantial advantages of soybeans, the need for them will continue to grow, which makes it necessary to improve existing and develop new technologies for their cultivation, considering local agroclimatic resources (Furman et al., 2022; Shovkova, 2022).

One of the determining factors for the formation of high and stable seed productivity of soybeans is mineral fertilisers and varietal characteristics, the share of which in the formation of the yield level reaches, respectively, 58.5-78.2 and 76.6% (Chynchyk, 2017). Pre-sowing seed inoculation can increase crop productivity by 50% or more (Kozar, 2015). Therewith, due to the symbiotic interaction with nodule bacteria,

the ability of soy to independently meet its need for nitrogen is at 25-75%, which substantially reduces the economic and environmental burden when growing it (Faridula et al., 2015; Chynchyk, 2017). However, the effectiveness of symbiosis largely depends on the complementarity of symbiotic partners, hydrothermal resources, nitrogen nutrition conditions, etc. (Patyka et al., 2015; Petrychenko et al., 2018).

Soybeans are a demanding crop for the availability of nutrients in the soil. For the formation of 1 centner of the seeds of its plant, according to Lykhochvor et al. (2016), 6.5-7.5 kg of nitrogen, 1.3-1.7 kg of phosphorus, and 1.8-2.2 kg of potassium are consumed. According to other researchers (Bahmat & Chynchyk, 2010; Melnyk & Romanko, 2015), the need for these macronutrients is even higher: nitrogen is needed in the amount of – 7.2-10.0 kg, phosphorus – 1.7-4.0 kg, potassium – 2.2-4.4 kg, which explains the positive reaction of soybeans to the application of mineral fertilisers in an easily accessible form. The greatest need of plants for nitrogen is due to the high

protein content of soy seeds. Due to their ability to assimilate atmospheric nitrogen in symbiosis with nitrogen-fixing nodule bacteria, soybeans can fix up to 180 kg/ha or more of biological nitrogen, which is also characterised by good assimilation by subsequent crops and no negative impact on ecological balance (Didora, 2018).

As a result, soybean plants can partially or completely meet their nitrogen needs, which allows growing them with only minimal doses of nitrogen fertilisers or their complete absence (Faridula, *et al.*, 2015; Didora, 2018;). However, the efficiency of fixing molecular nitrogen from the atmosphere due to the symbiotic interaction between soybean plants and nodule bacteria is not always high, which is due to the influence of various abiotic, biotic, and anthropogenic factors on them, for example, lack or excess of moisture, low or high temperatures, high acidity of the soil solution, mineral nutrition conditions, etc. (Petrychenko *et al.*, 2018). High symbiotic performance is provided only by a well-developed and highly active symbiotic apparatus (Patyka *et al.*, 2015; Petrychenko *et al.*, 2018), the formation of which largely depends on the reasonable selection of symbiotic partners (Patyka *et al.*, 2015; Nakei *et al.*, 2022), since microbial-plant interaction is not always characterised by high productivity in terms of the amount of fixed atmospheric nitrogen, which is associated with the high varietal specificity of soybeans to nodule bacterial strains (Petrychenko *et al.*, 2018; Didora, 2019).

An important agrotechnical measure that contributes to the formation of a highly productive soy-rhizobial symbiosis is the cultivation of soybeans based on bacterial and mineral nutrition (Chynchyk, 2017; Shovkova, 2022). For example, applying phosphorus-potassium fertilisers positively affects the increase in the number of nodules and the productivity of symbiosis in general (Ciampitti & Salvagiotti, 2018). As for the combined use of inoculants

and nitrogen minerals, the opinions of the scientific community are ambiguous (Faridula *et al.*, 2015; Kobak *et al.*, 2017; Chynchyk, 2017). It is believed that small starting doses of nitrogen, in the range of 15–30 kg/ha, have a positive effect on the process of nodule formation on the soybean roots in the initial growing season of plants (Patyka *et al.*, 2015; Furman *et al.*, 2022). Higher doses of nitrogen fertilisers inhibit the formation of the symbiotic system, reduce its effectiveness, and can lead to the complete termination of symbiotic relationships (Moldovan, 2018; Furman *et al.*, 2022;). The ambiguity of opinions regarding the feasibility of applying nitrogen fertilisers for soybeans is due to the complexity and multi-stage formation and functioning of various legume-rhizobial structures (Chekhova & Chekhov, 2019; Shevnikov *et al.*, 2022).

Effective use of the bioclimatic potential of the region in the cultivation of soybeans is possible only if the development and introduction into production of such technologies for its cultivation that maximally correspond to the genetic characteristics of the variety and consider the complex interaction of the plant organism with hydrothermal and soil resources (Petrychenko *et al.*, 2018; Shevnikov *et al.*, 2022).

Today, breeders have created many high-tech and highly productive soybean varieties, however, the level of realisation of their genetic potential of productivity is substantially determined by the soil and climatic conditions of a particular growing area and adapted cultivation technology, which is especially important in the context of climate change (Petrychenko *et al.*, 2018).

Since soybeans are characterised by a strong reaction to the length of the day, the most suitable for its cultivation is the geographical zone, the width of which is 160–240 km in the direction from South to North. The displacement of geographical space leads to changes in the duration of the vegetation period, productivity, qualitative

composition of seeds, adaptive properties, symbiotic productivity, and response to stress factors (Petrychenko *et al.*, 2018; Didora, 2019).

In this regard, an urgent and timely scientific task is to correct the technology of growing modern soybean varieties, considering the requirements of the culture for life factors.

The purpose of the study was to establish the influence of seed bacterisation and the norms and timing of mineral fertiliser application on the formation of symbiotic productivity of soybeans in the Forest-Steppe of Right-Bank Ukraine.

MATERIALS AND METHODS

The study was conducted during 2013-2015 in the experimental field of the state enterprise "Experimental Farm "Salivonkivske" of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine. The soil of the experimental site is typical low-humus chernozem with a humus content in the arable layer of 4.56%, easily hydrolysed nitrogen (DSTU 7863:2015, 2016) – 155-161 mg/kg of soil, mobile phosphorus (DSTU 4115-2002, 2003) – 44-54 mg/kg potassium exchange rate – 95-107 mg/kg of soil, the pH of salt extract is 6.7-7.2.

The field experiment was conducted according to the scheme: factor A – variety: Vilshanka (early-ripening) and Suziriia (medium-ripening) of selection of the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences"; Factor B – pre-sowing seed treatment: without inoculation, Phosphonitragine; factor C – fertiliser: without fertilisers (control), $P_{60}K_{60}$, $N_{15}P_{60}K_{60}$, $N_{30}P_{60}K_{60}$, $N_{45}P_{60}K_{60}$, $P_{60}K_{60} + N_{15}$, $N_{15}P_{60}K_{60} + N_{15}$, $N_{30}P_{60}K_{60} + N_{15}$.

Soybean sowing was conducted in the first half of May in a wide-row way with a row spacing of 45 cm when the soil warmed up at a seed depth of up to 10-12°C. The predecessor is winter wheat. The repetition is fourfold. Placement of options is systematic. Phosphorous and potash

fertilisers (granulated superphosphate and potash salt) were applied for the main tillage at the rate of $P_{60}K_{60}$; nitrogen (ammonium nitrate) – for pre-sowing cultivation and top dressing of soybean plants in the budding phase in accordance with the experiment scheme.

Seed inoculation was conducted on the day of sowing with a complex bacterial preparation for agricultural purposes certified in Ukraine – Phosphonitragine (developed by the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences"), which contains strains of nodule bacteria (*Br. japonicum*) and phosphatmobilising microorganisms (*B. mucilaginosus*). Seed bacterisation was conducted in accordance with the requirements specified in the recommendations for this type of work (Recommendations for effective application..., 1997). Since the seeds were treated with Maxim XL 035 FS mordant (1 L/t of seeds) 14 days before sowing, the bacterial load level was doubled and amounted to 400 thousand cells per 1 seed.

Planning of the experiment scheme, laying of the field experiment, placement of variants and repetitions was conducted in accordance with the requirements and recommendations set out in the manual "Fundamentals of scientific research in agronomy" (Yeshchenko, 2005). Sampling to determine the size of the symbiotic apparatus was conducted by the method of monoliths (Posypanov, 1993) in the main phenological phases of soybean development, the onset of which was determined by the visual method according to the "Methodology of State variety testing of agricultural crops" (2000).

The total number and mass of nodules, the number and mass of active nodules, the active symbiotic potential, and the amount of biologically fixed nitrogen were determined according to Posypanova (1993) methods.

Weather conditions during the years of the study were characterised by a substantial

difference both in years and in relation to long-term averages. In 2013, depending on the duration of the growing season of plants, their growth and development took place at an average daily temperature of 19.1-19.8°C, the sum of active temperatures (>10, °C) – 2036.3-2258.7°C and precipitation amounts – 251.4-334.0 mm. In 2014, the values of these indicators were, respectively, 18.6-19.5°C, 2020.4-2216.7°C, and 308.7-337.2 mm; in 2015 – 21.1-21.6°C, 2040.5-2324.4°C, and 135.3-166.5 mm. In general, in the last year of the study, the hydrothermal coefficient for the growing season was 0.6-0.7, while the optimal value for this crop was 1.0-1.7 (Petrychenko *et al.*, 2018).

RESULTS AND DISCUSSION

Analysis of the field experiment results indicates a positive influence of the examined technological methods of growing soybeans on the formation of its symbiotic apparatus. It was established that on the root system of plants of the Vilshanka and Suziriia varieties examined in the experiment, the number of nodules increased intensively before the onset of the phenological phase of seed filling, further on, with the approach of the physiological ripeness phase, their number gradually decreased (Table 1). This pattern was observed both in relation to the total number of root nodules and in relation to their active part.

Table 1. Dynamics of the number of nodules on the roots of soybean plants depending on inoculation and norms and terms of application of mineral fertilisers (average for 2013-2015), pcs./plant

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Vilshanka Variety							
Without fertilisers (control)	n/i	10.1	6.6	14.2	11.9	18.2	14.5
	i	25.1	20.5	29.6	25.2	39.8	34.6
P ₆₀ K ₆₀	n/i	13.5	10.2	19.4	17.1	25.4	21.2
	i	28.3	23.8	32.4	26.8	41.5	36.4
N ₁₅ P ₆₀ K ₆₀	n/i	16.0	12.5	21.1	17.9	26.2	23.5
	i	28.9	24.1	32.7	27.3	43.1	37.8
N ₃₀ P ₆₀ K ₆₀	n/i	19.2	15.6	22.2	18.2	31.5	27.3
	i	29.5	24.5	33.4	27.7	45.2	40.0
N ₄₅ P ₆₀ K ₆₀	n/i	12.6	8.4	17.8	13.2	24.5	19.4
	i	17.7	12.0	23.1	17.6	33.4	27.0
P ₆₀ K ₆₀ +N ₁₅	n/i	13.7	10.4	20.2	17.7	26.2	23.6
	i	28.2	23.7	32.6	27.1	44.3	38.6
N ₁₅ P ₆₀ K ₆₀ +N ₁₅	n/i	16.2	12.7	22.8	19.4	33.2	29.4
	i	28.7	23.8	34.3	29.0	50.0	42.8
N ₃₀ P ₆₀ K ₆₀ +N ₁₅	n/i	19.4	15.8	25.2	20.8	34.5	30.0
	i	29.0	23.6	35.4	29.4	51.3	43.3
Suziriia variety							
Without fertilisers (control)	n/i	11.8	8.1	20.5	18.1	24.5	20.7
	i	26.7	22.2	38.1	34.8	48.3	42.8
P ₆₀ K ₆₀	n/i	15.9	12.4	26.3	24.2	33.1	28.7
	i	30.8	26.5	41.6	36.1	52.2	47.3
N ₁₅ P ₆₀ K ₆₀	n/i	21.1	17.6	29.1	25.7	35.2	31.3
	i	32.6	27.6	43.2	37.5	53.0	47.8

Table 1, Continued

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Suziriia variety							
$N_{30}P_{60}K_{60}$	n/i	25.2	21.4	32.2	27.9	38.4	33.9
	i	35.6	30.4	44.8	38.7	54.1	48.3
$N_{45}P_{60}K_{60}$	n/i	14.7	10.1	25.7	21.6	29.3	24.0
	i	21.1	16.7	33.6	26.4	40.9	33.8
$P_{60}K_{60} + N_{15}$	n/i	16.0	12.6	27.1	24.7	36.0	32.3
	i	30.8	26.0	42.8	36.6	53.8	48.0
$N_{15}P_{60}K_{60} + N_{15}$	n/i	21.0	17.4	33.2	29.7	40.2	35.9
	i	32.3	27.2	46.1	40.7	56.5	50.3
$N_{30}P_{60}K_{60} + N_{15}$	n/i	24.9	21.1	34.6	29.9	41.4	36.8
	i	35.2	29.6	47.2	41.0	57.1	51.0
HIP _{0.05} total		3.44		4.05		5.21	
HIP _{0.05} variety		1.23		1.39		1.56	
HIP _{0.05} fertiliser		2.57		3.08		3.46	
HIP _{0.05} inoculation		1.23		1.39		1.56	

Note: *n/i – seeds with no inoculation; i – inoculated seeds

Thus, in the budding phase, the total number of nodules on plants of the control variant was 10.1 pcs./plant in the Vilshanka variety and 11.8 pcs./plant in the Suziriia variety, of which there were 6.6 and 8.1 active nodules on one plant, respectively. Improvement of phosphorus-potassium nutrition conditions due to the introduction of $P_{60}K_{60}$ contributed to an increase in the total number of nodules – by 3.4-4.1 pcs./plant, depending on the variety, including their active part – by 3.6 and 4.3 pcs./plant. A more intensive increase in the number of root nodules was observed when applying full mineral fertiliser – by 2.5-13.1 (total number) and 1.8-13.4 pcs./plant (active bulbs). However, the effect of such fertiliser on the formation of a symbiotic apparatus varied substantially depending on the norms and timing of nitrogen fertiliser application.

It was determined that small starting doses of nitrogen are within the limits of N_{15-30} had a pos-

itive effect on the formation of root nodules, the total number of which increased by 58.4-113.6%, of which the active part – by 89.3-164.2%. The application of N_{45} against the background of $P_{60}K_{60}$ had a positive, but not so pronounced effect, as a result of which the increase in the total number of nodules relative to absolute control in the Vilshanka variety was only 24.8%, in the Suziriia variety – 24.6%, including active ones, respectively, 27.3 and 24.7%. The intensity and size of the symbiotic apparatus were determined by inoculation with Phosphonitragine rather than by applying mineral fertilisers. Pre-sowing bacterisation of soybean seeds with a complex preparation containing *Br. japonicum* and *B. Mucilaginosa* stains provided an increase in the total number of nodules and their active component in the early-ripening Vilshanka variety, respectively, by 148.5 and 210.1%, in the medium-ripening Suziriia variety – by 126.3 and 174.1%.

The most effective agricultural method for the formation of a well-developed symbiotic system in plants of the examined soybean varieties was the combined effect of seed inoculation and mineral fertilisers with the norm of $N_{30}P_{60}K_{60}$. The interaction of these factors provided an increase in the total number of root nodules in the Vilshanka variety by 192.1%, and in the Suziriia variety – by 201.7%, of which active ones – by 271.2 and 275.3%, respectively.

Before the onset of the seed filling phase, when the symbiotic apparatus of soybeans reached its maximum development, there was a certain redistribution between the variants of the experiment. As at the first stages of soy-rhizobial symbiosis formation, the smallest number of nodules was formed in areas of absolute control (without inoculation and mineral fertilisers) – 18.2 pieces were formed in the Vilshanka variety per plant, in the Suziriia variety – 24.5 pcs./plant. Among all other variants of the experiment scheme, the least developed symbiotic apparatus was in plants grown in areas where $N_{45}P_{60}K_{60}$ was applied – the increase in the total number of nodules and their active part was 4.8-6.3 and 3.3-4.9 pcs./plant or 19.6-34.6 and 16.0-3.8%, respectively. Investigating the interaction of mineral fertiliser and bacterisation factors, it was established that the smallest increase in root nodules was also noted for the

introduction of $N_{45}P_{60}K_{60}$ – 15.2-16.4 pcs./plant (total quantity) and 12.5-13.1 pcs./plant (active ingredients) or 67.0-83.5 and 63.3-86.2%, respectively. Of all the fertiliser options, the separate application of nitrogen fertilisers against the background of $P_{60}K_{60}$ had the most positive effect on the formation of root nodules, both with and without inoculation.

The most favourable conditions for the formation of root nodules were formed according to the technological model of soybean cultivation, which provided for inoculation of seeds with a complex bacterial preparation containing nodule bacteria and fosformobilising microorganisms and the introduction of $N_{30}P_{60}K_{60} + N_{15}$. In this variant, the increase in the total number of root nodules and their active part in the Vilshanka variety was 33.1 and 28.8 pcs./plant or 181.9 and 198.6%, respectively. The Suziriia variety had a similar relationship – 32.6 and 30.3 pcs./plant or 133.1 and 146.9%.

An important characteristic of the process of formation of the symbiotic apparatus of soybeans is the mass of root nodules (Table. 2). According to the average research results, it was established that the dynamics of the formation of the total mass of nodules and their active part, depending on the action and interaction of the examined factors, was similar to the dynamics of changes in their number.

Table 2. Dynamics of the raw mass of nodules on the roots of soybean plants depending on inoculation and the norms and terms of mineral fertiliser application (average for 2013-2015), g/plant

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Vilshanka Variety							
Without fertilisers (control)	n/i	0.29	0.19	0.45	0.39	0.61	0.51
	i	0.67	0.46	0.97	0.85	1.27	1.07
$P_{60}K_{60}$	n/i	0.34	0.23	0.58	0.52	0.78	0.66
	i	0.75	0.51	1.04	0.92	1.32	1.12
$N_{15}P_{60}K_{60}$	n/i	0.41	0.28	0.65	0.59	0.86	0.73
	i	0.79	0.56	1.06	0.96	1.36	1.16

Table 2, Continued

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Vilshanka Variety							
$N_{30}P_{60}K_{60}$	n/i	0.52	0.36	0.77	0.70	0.92	0.78
	i	0.84	0.58	1.08	0.98	1.39	1.19
$N_{45}P_{60}K_{60}$	n/i	0.30	0.20	0.53	0.46	0.73	0.60
	i	0.47	0.28	0.80	0.69	0.97	0.78
$P_{60}K_{60} + N_{15}$	n/i	0.36	0.24	0.63	0.56	0.87	0.75
	i	0.76	0.50	1.05	0.94	1.37	1.17
$N_{15}P_{60}K_{60} + N_{15}$	n/i	0.43	0.30	0.79	0.72	0.95	0.81
	i	0.77	0.54	1.10	1.01	1.43	1.23
$N_{30}P_{60}K_{60} + N_{15}$	n/i	0.54	0.38	0.86	0.80	0.97	0.83
	i	0.82	0.55	1.14	1.06	1.45	1.26
Suziriia variety							
Without fertilisers (control)	n/i	0.33	0.22	0.61	0.52	0.77	0.63
	i	0.78	0.53	1.23	1.07	1.49	1.22
$P_{60}K_{60}$	n/i	0.38	0.26	0.84	0.72	0.87	0.72
	i	0.84	0.58	1.30	1.15	1.61	1.33
$N_{15}P_{60}K_{60}$	n/i	0.56	0.39	0.93	0.84	0.98	0.81
	i	0.90	0.64	1.37	1.23	1.68	1.39
$N_{30}P_{60}K_{60}$	n/i	0.68	0.48	1.05	0.93	1.11	0.92
	i	0.95	0.70	1.43	1.28	1.75	1.46
$N_{45}P_{60}K_{60}$	n/i	0.35	0.23	0.78	0.67	0.83	0.68
	i	0.54	0.37	1.10	0.93	1.24	0.98
$P_{60}K_{60} + N_{15}$	n/i	0.39	0.27	0.87	0.77	1.00	0.83
	i	0.84	0.56	1.33	1.18	1.71	1.42
$N_{15}P_{60}K_{60} + N_{15}$	n/i	0.53	0.38	1.09	0.96	1.21	1.01
	i	0.89	0.61	1.47	1.33	1.81	1.52
$N_{30}P_{60}K_{60} + N_{15}$	n/i	0.67	0.46	1.15	1.05	1.29	1.07
	i	0.91	0.66	1.52	1.39	1.84	1.56
HIP _{0.05} total		0.10		0.13		0.12	
HIP _{0.05} variety		0.03		0.05		0.04	
HIP _{0.05} fertiliser		0.06		0.08		0.09	
HIP _{0.05} inoculation		0.03		0.05		0.04	

Note: *n/i – seeds with no inoculation; i – inoculated seeds

In the budding phase, the total mass of all nodules ranged from 0.29-0.95 g/plant, of which active ones – 0.19-0.70 g/plant. The lowest total mass of nodules and their active part was observed on the roots of plants from the control areas – 0.29-0.33 and 0.19-0.22 g/plant, depending on the variety. The most powerful symbiotic apparatus by weight with a total mass of

nodules of 0.84-0.95 g/plant, including active 0.58-0.70 g/plant, was formed due to the interaction of inoculation factors and the application of a complete mineral fertiliser in normal $N_{30}P_{60}K_{60}$. The increase in the mass of nodule formations relative to the control was, respectively, 187.9-189.7 and 205.3-218.2%. An increase in the mass of root nodules, and their number,

was observed before the onset of the phenological phase of seed filling, during which the total mass of nodules reached 0.61-1.84 g/plant, including active ones – up to 0.51-1.56 g/plant.

All the examined variants of technological techniques contributed to an increase in the mass of nodules. The interaction of inoculation factors and separate application of nitrogen fertilisers N_{30-45} had the most positive effect on the process of mass formation of the symbiotic apparatus against the background of $P_{60}K_{60}$. The maximum total mass of nodules – at the level of 1.45-1.84 g/plant and their active part – in the range of 1.26-1.56 g/plant was noted at the experiment site, where pre-sowing bacterisation of seeds was conducted with a bacterial preparation containing *Br. japonicum* and *B. Mucilaginosus* and with the application of $N_{30}P_{60}K_{60} + N_{15}$. The increase to control was 137.7-139.0 and 147.1-147.6%, respectively. Both in terms of the number and mass of all the bulbs of more powerful ones,

the symbiotic apparatus formed a medium-ripening Suziriia variety.

An important indicator of the effectiveness of legume-rhizobial symbiosis is the active symbiotic potential, which lasts from the appearance to the destruction of leghemoglobin in root nodules (Patyka, 2015; Kobak, 2017; Furman, 2022). Seed inoculation with Phosphonitragine and mineral fertilisers had a positive effect on the efficiency of interaction between micro- and macrosymbionts (Table 3). The most effective symbiotic relationships were for seed bacterisation and, accordingly, more intensive colonisation of soybean plant roots with symbiotic bacteria. As a result, the increase in the active symbiotic potential in relation to control for the period from the budding phase to the onset of physiological ripeness of seeds in the Vilshanka variety was 4.81 thousand kg-days/ha, in the Suziriia variety – 5.46 thousand kg-days/ha or 47.8 and 46.7%, respectively.

Table 3. Efficiency of symbiotic nitrogen fixation of soybeans depending on the influence of organised factors (average for 2013-2015), kg/ha

Fertiliser	Inoculation	Vilshanka		Suziriia	
		active symbiotic potential, thousand kg-day/ha	amount of fixed nitrogen, kg/ha	active symbiotic potential, thousand kg-day/ha	amount of fixed nitrogen, kg/ha
Without fertilisers (control)	n/i	10.06	65.1 + 7.7**	11.69	70.9 + 10.6
	i	14.87	99.2 + 14.4	17.15	104.3 + 13.6
$P_{60}K_{60}$	n/i	11.21	68.0 + 9.4	13.04	74.2 + 9.4
	i	16.04	106.3 + 13.0	18.55	112.5 + 14.8
$N_{15}P_{60}K_{60}$	n/i	12.11	70.2 + 8.7	14.10	75.5 + 7.6
	i	16.63	108.4 + 14.0	19.75	118.2 + 18.2
$N_{30}P_{60}K_{60}$	n/i	13.06	73.9 + 8.7	15.15	76.5 + 10.8
	i	17.27	112.4 + 15.5	20.51	121.3 + 19.2
$N_{45}P_{60}K_{60}$	n/i	10.50	68.9 + 9.6	12.29	71.8 + 7.2
	i	12.87	103.8 + 15.4	14.40	107.1 + 18.5
$P_{60}K_{60} + N_{15}$	n/i	11.98	71.8 + 10.1	13.84	76.0 + 10.9
	i	16.43	110.8 + 15.7	19.43	120.9 + 20.5
$N_{15}P_{60}K_{60} + N_{15}$	n/i	13.31	78.2 + 10.8	15.75	78.8 + 9.8
	i	17.82	118.8 + 20.6	21.30	127.1 + 22.1
$N_{30}P_{60}K_{60} + N_{15}$	n/i	14.11	80.1 + 10.1	16.28	81.0 + 10.0
	i	18.40	124.2 + 19.9	22.23	130.3 + 21.2

Table 3, Continued

Fertiliser	Inoculation	Vilshanka		Suziriia	
		active symbiotic potential, thousand kg·day/ha	amount of fixed nitrogen, kg/ha	active symbiotic potential, thousand kg·day/ha	amount of fixed nitrogen, kg/ha
HIP _{0.05} total		1.05			1.05
HIP _{0.05} variety		0.52	–	–	0.52
HIP _{0.05} fertiliser		0.87			0.87
HIP _{0.05} inoculation		0.52			0.52

Note: *n/i – seeds with no inoculation; i – inoculated seeds; ** M ± m – reliability interval of the arithmetic mean at the 5% substantiality level

The effectiveness of applying mineral fertilisers in the experiment was substantially determined by the norms and terms of applying nitrogen fertilisers against the background of P₆₀K₆₀. The least effective was a one-time application of N₄₅ as a result, the increase in the active symbiotic potential relative to the control did not exceed 4.4-5.1%, depending on the variety. However, the introduction of the same nitrogen rate by retail method, on the contrary, provided maximum efficiency of legume-rhizobial symbiosis – the symbiotic potential increased by 39.2-40.3%.

According to this indicator, the best option in the experiment was the one where a combination of technological methods of inoculation and application was examined N₃₀P₆₀K₆₀ + N₁₅ – the growth of active symbiotic potential reached 82.9-90.2%. The highest symbiotic activity is characteristic of the Suziriia variety.

The productivity of legume-rhizobial symbiosis is characterised by the amount of symbiotically fixed nitrogen, for calculations of the accumulation volumes of which data on the active symbiotic potential and specific active symbiosis were used (Posypanov, 1993). Soybean crops on control variants were the least symbiotically productive – 65.1-70.9 kg/ha, depending on the variety. Inoculation of seeds with a bacterial preparation provided an increase in the volume of biological nitrogen accumulation by 47.1-52.4% to the level of 99.2-104.3 kg/ha.

The application of mineral fertilisers, in comparison with bacterisation, affected the productivity of nitrogen fixation less effectively – in the Vilshanka variety, the increase was 4.5-23.0%, in the Suziriia variety – 4.7-14.2%. Of all the variants of the experiment, where the influence of the norms of complete mineral fertiliser on symbiotic productivity was examined, the lowest values were obtained for applying N₄₅P₆₀K₆₀ – 68.9-71.8 kg/ha, which almost did not differ from the values obtained on the variants where only phosphorus-potassium fertiliser was conducted – 68.0-74.2 kg/ha.

The most intense accumulation of symbiotically fixed nitrogen occurred due to the interaction of technological measures of seed bacterisation with Phosphonitragin and retail application of nitrogen fertilisers in the norm N₃₀₋₄₅ against the background of P₆₀K₆₀ – 118.8-130.3 t/ha, which exceeded the control by 71.3-75.6%.

The intensity of development and the level of productivity of the soybean symbiotic apparatus are substantially determined by technological factors (Melynyk & Romanko, 2015; Petrychenko et al., 2018; Didora et al., 2019). Among the factors that most affect the formation and functioning of root nodules, most researchers distinguish inoculation and mineral fertilisers (Didora, 2018; Furman et al., 2022). Thus, according to the results of the studies by Chynchyk (2017), before the onset of the seed filling phase,

inoculation provided an increase in the raw mass of nodules with leghemoglobin at the level of 0.126-0.140 g/plant, depending on the variety, fertiliser application – 0.019-0.034 g/plant, while the difference between varieties in this indicator did not exceed 0.002 g/plant. According to V.F. Kaminsky (2006), pre-sowing bacterisation of seeds provided an increase in the mass of active nodules in the range of 0.15-0.35 g/plant and their number in the basal part of the root – 22-29 pcs./plant. Kots & Mamenko (2015) note that in plants inoculated 7 days before sowing, the mass of nodules in the stage of 3 real leaves exceeded the control by 1.5-2.0 times. In the experiments of O. Temriienko (2018), fertilisation and seed inoculation provided an increase in the number of active nodules by 14.7-18.3 pcs./plant or 76-77%, while the difference between the varieties on the control variants did not exceed 7.3 pcs./plant. The same pattern was observed in relation to the mass of active nodules. The results obtained in this study confirm the data of these researchers (Temriienko, 2018; Furman *et al.*, 2022). It was established that in the budding phase due to inoculation, the increase in the number and mass of active nodules was 13.9-14.1 pcs./plant and 0.27-0.31 g/plant, due to mineral fertiliser – respectively, 3.6-13.0 pcs./plant and 0.04-0.24 g/plant, while the difference between the varieties in the control variants did not exceed 1.5 pcs./plant and 0.03 g/plant. Thus, the pattern was observed before the onset of the seed filling phase.

The presented results of the study also show a positive effect on the formation of the symbiotic apparatus of phosphorus-potassium fertilisers, the introduction of which in a dose of $P_{60}K_{60}$ against the background of inoculation, provided an increase in the number and mass of active nodules in the seed filling phase in the range of 1.8-4.5 pcs./plant and 0.05-0.11 g/plant relative to variants where only inoculation was performed. The obtained data are confirmed in

the experiments of Gamaiunova & Nazarchuk (2013), who note that the application of phosphorus-potassium fertilisers in the norm of $P_{45}K_{60}$ in combination with bacterisation of soybean seeds, compared only with bacterisation, provided an increase in the number of active nodules on plant roots by 40-81.8%.

More substantial increases in both the mass of active root nodules and their number were noted for the combination of inoculation and full mineral fertiliser application. Moreover, the size of the symbiotic apparatus was most influenced by the norms and timing of nitrogen fertilisers, the importance of which in soybean cultivation is the most controversial agrotechnical measure (Faridula *et al.*, 2015; Chynchyk, 2017). According to the results presented in the study, the smallest increase in the number and mass of active nodules both on non-inoculated plants and during pre-sowing seed inoculation was observed with a separate application of nitrogen fertilisers in a dose of N_{45} against the background of $P_{45}K_{60}$. The symbiotic apparatus was most developed under the condition of the interaction of seed bacterisation factors and the introduction of low doses of nitrogen fertilisers – N_{15-30} against the background of $P_{60}K_{60}$. These data confirm the scientific statement of many researchers (Li, 2020) on the positive effect of low doses of nitrogen fertilisers on the formation of root nodules on soybean roots.

A valuable result of this study is the confirmed positive effect of separate application of nitrogen fertilisers on the formation of the soybean symbiotic apparatus. It is established that nitrogen fertilisers applied in the norm N_{45} during pre-sowing cultivation and in the budding phase of plants in combination with technological measures of seed bacterisation ensures the formation of the most developed symbiotic apparatus. The increase in the number and mass of active nodules from the use of such a technological model, compared with a single application

of the same nitrogen rate, is 16.3-17.2 pcs./plant and 0.48-0.58 g/plant. The results obtained in the study are confirmed by F.R. Bender *et al.* (2022) and V. Didora *et al.* (2019).

It is established that the technological model that contributes to the formation of the most developed symbiotic apparatus ensures the accumulation of the maximum amount of biological nitrogen. The higher efficiency of legume-rhizobial symbiosis is determined by fertilisation and inoculation than the varietal characteristics of soybeans, which is confirmed by the results of the studies by other researchers who have examined the influence of technological techniques on the effectiveness of soybean symbiosis (Bender *et al.*, 2022). The presented study states that the difference between the examined soybean varieties in terms of the level of biological nitrogen accumulation was insubstantial and did not exceed 5.8 kg/ha. Inoculation of seeds of the early-ripening Vilshanka variety and the medium-ripening Suziriia variety provided an increase in biological nitrogen at the level of 33.4-34.1 kg/ha. The addition of a complete mineral fertiliser against the background of seed bacterisation increased the increase in accumulated atmospheric nitrogen by 43.3-59.4 kg/ha. Other researchers also note a more substantial positive effect of applying a complete mineral fertiliser compared to inoculation on the process of atmospheric nitrogen accumulation. According to V.F. Didora *et al.* (2019) when growing soybeans in the absence of mineral fertiliser, seed inoculation contributed to the accumulation of 82.3 kg/ha, the introduction of $N_{60}P_{60}K_{60}$ increased this volume of biological nitrogen by 46.1 kg/ha. Thus, bacterial and mineral nutrition is an important factor influencing the formation and productivity of the soybean symbiotic apparatus, which is a substantial factor in enriching the soil with biological nitrogen.

CONCLUSIONS

As a result of the study, it was established that growing soybeans based on reasonable bacterial and mineral nutrition in the conditions of the right-bank Forest-Steppe of Ukraine on typical low-humus chernozem allows forming a highly productive soy-rhizobial symbiosis. The effectiveness of the symbiotic system was largely determined by the norms and timing of nitrogen fertiliser application against the background of phosphorus-potassium fertiliser and inoculation. The application of only phosphorus-potash fertilisers, although had a positive effect on the formation of the number and mass of root nodules, the size and efficiency of the symbiotic apparatus with the addition of a complete mineral fertiliser were substantially higher both inoculation and in its absence. With the application of $P_{60}K_{60}$, the number of active nodules in the budding phase increased – by 3.6-4.3 pcs./plant, depending on the variety, for applying full mineral fertiliser – by 1.8-13.4 pcs./plant. With a separate application of nitrogen fertilisers, small starting doses of nitrogen were more effective – within the limits of N_{15-30} , which provided an increase in the number of active bulbs by 89.3-164.2%, with the application of N_{45} against the background of $P_{60}K_{60}$, the number of active bulbs increased only by 24.7-27.3%. Inoculation with a complex preparation, containing *Br. japonicum* and *B. Mucilaginosus* strains provided an increase in the number of active nodules by 174.1-210.1%. The interaction of fertiliser and inoculation factors increased the increase in the number of active root nodules by 271.2-275.3%. The most favourable conditions for the formation of a well-developed symbiotic apparatus on the root systems of soybean plants of Vilshanka and Suziriia are obtained according to the technological model of their cultivation, which provided for inoculation of seeds with a bacterial preparation containing nodule

bacteria and fosformobilising microorganisms and the introduction of $N_{30}P_{60}K_{60} + N_{15}$ in the budding phase. The interaction of these technological techniques provided an increase in the number of active root nodules in an early-ripening variety by 198.6%, and in a medium-ripening variety – by 146.9%. Similar patterns were observed in the mass of active root nodules, the increase in control on this variant was 147.0-147.6%, and the level of active symbiotic potential, the increase of which reached 82.9-90.2%. In all variants of the experiment, the highest symbiotic activity is characteristic of the variety Suziriia. Application of full mineral fertiliser in the norm of $N_{30}P_{60}K_{60} + N_{15}$ and conducting pre-sowing seed bacterisation with the preparation based

on strains of nodule bacteria and fosformobilising microorganisms provided the highest productivity of symbiotic systems in terms of the volume of accumulation of symbiotically fixed nitrogen – in the early-ripening soybean variety Vilshanka – 124.2 kg/ha, in the medium-ripening variety Suziriia – 130.3 kg/ha. Further research will be aimed at investigating the effect of bacterial and mineral fertiliser on the formation of highly productive soybean crops.

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CONFLICT OF INTERESTS

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Симбіотична продуктивність сої залежно від інокуляції та удобрення в умовах Правобережного Лісостепу

Анотація. Враховуючи високу цінність біохімічного складу насіння сої та універсальність використання цієї культури, потреби в ній і надалі зростатимуть, що обумовлює необхідність удосконалення існуючих та розробку нових технологій її вирощування з урахуванням

місцевих агрокліматичних ресурсів. Тому, на сьогодні дослідження, спрямовані на вивчення агроекологічних основ використання хімічних та біологічних прийомів у сучасних технологіях вирощування сої є актуальними. Метою досліджень було виявити особливості формування симбіотичної продуктивності сої під впливом бактеріально-мінерального удобрення в умовах правобережного Лісостепу України. Для досягнення мети було закладено польовий метод за розробленою схемою. Встановлено позитивний вплив мінерального удобрення та інокуляції на формування симбіотичного апарату сої та його продуктивність. Найменший приріст кількості корневих бульбочок відмічали за внесення $N_{45}P_{60}K_{60}$ – 24,7-27,3 % залежно від сорту. Більш ефективними були невеликі стартові дози азоту – у межах N_{15-30} – вони забезпечували приріст кількості активних бульбочок на 51,2-106,9 %. Бактеризація насіння комплексним бактеріальним препаратом Фосфонітрагін збільшувала кількість активних бульбочок на коренях сої на 106,8-138,6 % залежно від сорту. Взаємодія технологічних прийомів мінерального удобрення та інокуляції сприяла зростанню як кількості бульбочок з леггемоглобіном – на 128,5-198,6 %, так і їх маси – на 111,1-147,6 %. Максимального розвитку симбіотичний апарат сої досягав при взаємодії факторів інокуляції насіння бактеріальним препаратом, що містить штами містить штами *B. japonicum* і *B. mucilaginosus* та внесення $N_{30}P_{60}K_{60} + N_{15}$ у фазі бутонізації. Така технологічна модель вирощування культури забезпечила найвищу продуктивність бобово-ризобіального симбіозу рослин сої за обсягами накопичення симбіотично фіксованого азоту – у скоростиглого сорту сої Вільшанка – 124,2 кг/га, у середньостиглого сорту Сузір'я – 130,3 кг/га. Практичне значення одержаних результатів досліджень полягає в удосконаленні сортових технологій вирощування сої на основі комплексного застосування інокуляції насіння бактеріальним препаратом та внесення азотних добрив в роздрібний спосіб на фоні фосфорно-калійного удобрення

Ключові слова: мінеральне добриво; сорт; симбіотичний апарат; активний симбіотичний потенціал; біологічний азот

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Humus and nitrogen content of sod-podzolic soil under the influence of biopreparations for potato cultivation

Abstract. In organic potato cultivation technologies, various biopreparations are used, which have a considerable impact on both the growth and development of crops, and on soil fertility indicators, which is especially important for sod-podzolic soils characterised by low potential fertility. The purpose of the study is to establish the changes in humus content and mineral nitrogen in sod-medium-podzolic loam soil under the influence of biopreparations for the decomposition of white mustard as a cover crop and for the treatment of potato tubers and vegetative potato plants. In a two-factor experiment, the following factors were examined: factor 1: control without a destructor and “Ecostern” destructor at a dosage of 1.2 litres per hectare; factor 2: nine options of biopreparations application, including Agat, Regoplant, Mycohelp, Phytohelp, and Stimpo. Soil samples were collected from the 0-30 cm layer of sod-medium-podzolic sandy loam soil on water-glacial deposits. In them, the total humus content was established by the Tyurin method, and the mineral nitrogen content was calculated as the sum of ammonium and nitrate nitrogen determined potentiometrically. The application of the

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destructor on the green biomass of the cover crop contributed to an increase in the humus content in the 0-30 cm soil layer, where it ranged from 1.135% to 1.24%, compared to 1.025% to 1.15% in the options without the use of the bio-destructor. A reverse dependence was observed in terms of mineral nitrogen content. In the options with the use of the Ecostern destructor, the mineral nitrogen content was on average 2.09 mg/kg lower compared to the options without the application of the destructor. The highest humus content was observed in option 8, which involved the use of “Phytohelp” for treating potato tubers at a dosage of 1.0 litre per ton and three-fold treatment by “Phytohelp” at a dosage of 1.0 litre per hectare during the vegetation period. In the option without the destructor, the humus content was 1.15% and 1.24% with the application of the Ecostern bio-destructor. It slightly lagged behind option 9 with the “Phytohelp” biopreparations. The materials presented in the study may have practical value for agricultural enterprises engaged in growing organic potatoes to ensure the preservation and reproduction of organic matter in soils

Keywords: fertility; organic cultivation techniques; humification; microorganisms; destructor; cover crops

INTRODUCTION

In Ukraine, the soil cover undergoes a devastating effect of dehumidification, reflected, primarily, in a decrease in the humus content, which is why research is relevant to find ways to preserve and restore its content in soils. Carbon is not only the main element that is part of humus but also an element of plant nutrition. In addition, it is a source of providing plants with other nutrients, affects the processes of nitrogen fixation, mineralisation and immobilisation, denitrification, and is an important source of energy for microorganisms (Demydenko & Velychko, 2019). Under the conditions of the Central Forest-Steppe region of Ukraine, researchers have found that in a short-duration crop rotation, the most optimal ratio between organic carbon and nitrogen is 30:1. This ratio ensures the predominance of humification processes over mineralisation in strongly degraded low-humus podzolic black soils. This ratio ensured the achievement of a positive balance of humus. Intensity of nitrogen transformation processes can be considered as an indicator of the state of agroecosystems under the influence of biotic or abiotic factors (Volkogon *et al.*, 2014).

Indeed, due to these reasons, researchers pay special attention to organic and biological farming systems, which aim to reduce anthropogenic stress and, consequently, preserve soil fertility. Le-Le Su *et al.* (2023) emphasise that in modern agricultural production, a serious challenge is to ensure the preservation of high productivity of agrocenoses and reduce carbon dioxide emissions from soils while reducing the amount of mineral fertilisers applied. Researchers conducted a field experiment to assess the impact of an intermediate cover crop with reduced nitrogen content on the yield of maize and the reduction of carbon emissions in northwest China. It was established that the use of green manure as a component of intermediate cover crops in maize cultivation, along with a reduction in the amount of nitrogen fertilisers, increases maize productivity and mitigates carbon emissions on agricultural land.

V. Petrychenko *et al.* (2018) draw attention to the high level of grain exports from Ukraine, which can create even greater problems with soil fertility since the removed plant nutrients

are not returned to the soil. Sod-podzolic soils are characterised by a low content of humus and nutrients, especially nitrogen, so to increase the productivity of such soils, special attention should be paid to the application of fertilisers and land reclamation agents.

O.V. Menyailo *et al.* (2018) concluded that the optimal ratio of carbon to nitrogen is 30:1, because it creates the best conditions for humification and slowing down the mineralisation of organic matter in the soil. Such conditions were created with an organic fertiliser system in a short-term crop rotation. Increasing the reserves of organic carbon available to various microorganisms under different fertiliser systems is an effective way to regulate the carbon-nitrogen balance of soils.

According to V. Volkogon *et al.* (2020), the exclusive use of mineral fertilisers for cultivating table potatoes is deemed ineffective from an ecological standpoint, as it leads to the highest specific losses of N_2O . Therefore, it is preferable to combine mineral fertilisers with the addition of straw, cover crops such as lupine or manure. Moreover, an increase in fertiliser rates accelerates the processes of nitrogen mineralisation.

J.F. Püspök *et al.* (2020) established that soil nitrogen enrichment did not affect the accumulation of carbon fractions. The high supply of calcium in the soil increased mineral-associated organic matter (MAOM) by 58%.

Thus, long-term organic-mineral fertilisation affects humification processes, specifically the formation of humic acids. The HA/FA ratio was found to be 0.28 in the control without fertilisers, compared to 0.33-0.88 in the fertiliser-treated options with lime application (Skrylnyk *et al.*, 2022).

The humus status of soils affects the structural condition, soil pH, indicators of microbial activity, and other factors. Therewith, the quantity and quality of organic matter vary across

soil-climatic zones (Tonkha *et al.*, 2019). Therefore, research on changes in the humus status of soils under different crop cultivation practices is important. The purpose of the study is to establish changes in the content of humus and nitrogen compounds under the influence of bio-preparations for potato tuber treatment, and the use of a destructor for better decomposition of cover crop.

MATERIALS AND METHODS

The studies mentioned above were conducted from 2020 to 2022 at the Volynska State Agricultural Research Station of the Institute of Potato Growing of the National Academy of Agrarian Sciences of Ukraine. Experiments were conducted on sod-medium-podzolic sandy loam soil to examine potato cultivation. The examined potato variety – Partner, is a medium-early table variety of Ukrainian selection, which has a growing season of 107 days.

Two factors were examined in the experiment: factor A included two options, namely control (white mustard green manure without a destructor) and factor B – introduction of 1.2 L/ha of Ecostern bio-destructor for better decomposition of green manure.

The options for Factor B include: treatment of tubers with biopreparations and three-time treatment of vegetative plants with biopreparations.

1. Control (without introducing biopreparations).

2. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during the growing season with Agate 25 – 100 ml/ha.

3. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during the growing season with Regoplant – 50 ml/ha.

4. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during the growing season with Phytohelp – 1.0 L/ha.

5. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during the growing season with Stimpo – 15 ml/ha.

6. Treatment of tubers with Mycohelp – 2.0 L/t and three-time treatment with Mycohelp – 1.0 L/ha during the growing season.

7. Treatment of tubers with 50 ml/t of Regoplant and three-time treatment with Regoplant 50 ml/ha during the growing season.

8. Application of Phytohelp for processing tubers at a dose of 1.0 L/t and three-time treatment with Phytohelp at a dose of 1.0 L/ha during the growing season.

9. Treatment of tubers with Stimpo – 15 ml/t and three-time treatment with 15 ml/ha of Stimpo during the growing season.

Mycohelp contains a mixture of *Bacillus subtilis*, *Azotobacter*, *Enterobacter*, *Enterococcus* bacterial cells and *Trichoderma lignorum*, *Trichoderma viride* fungi, has the total number of viable effective microorganisms 1.0×10^9 CFU/g.

The active substance of Regoplant contains a complex of biologically active compounds – products of vital activity of micromycete fungi – 0.3 g/L (saturated and unsaturated fatty acids (C14-C28), polysaccharides, 15 amino acids, analogues of phytohormones of cytokinin and auxin nature).

The preparation Agate consists of *Pseudomonas aureofaciens* inactivated bacteria of H16 strain, 2% + biologically active substances of the culture liquid, 38%, biofungicide Phytohelp from the cell of *Bacillus subtilis* bacteria, titer 1.0×10^9 – 1.0×10^{10} CFU/cm³. Stimpo contains a complex of biologically active compounds – products of vital activity of micromycete fungi – 1 g/L (saturated and unsaturated fatty acids, polysaccharides, 15 amino acids, analogues of phytohormones of cytokinin and auxin nature).

Soil samples from the experimental options were taken in a threefold repetition in the

phases of germination, flowering, and maturation of table potatoes from layers of 0-10, 10-20, and 20-30 cm for DSTU 4287:2004. Their humus content was determined according to the Tyurin method (DSTU 4289:2004, 2005). The mineral nitrogen content was calculated as the sum of the nitrate and ammonium nitrogen content, which was determined potentiometrically according to DSTU 4725: 2007 (2008).

RESULTS AND DISCUSSION

The use of biopreparations allows for obtaining environmentally safe products and restoring soil fertility. Among such fertilisers, destructors that accelerate the decomposition of plant residues are important (Kovalenko *et al.*, 2020). The microorganisms that make up their composition are symbiotic, they improve the nitrogen, phosphorus, and potassium nutrition of plants (Bogovin, 2009).

The humus content in sod-podzolic soil varied depending on the biopreparations used (Fig. 1).

Not only the humus content in the soil is important, but also its assessment. According to DSTU 4362:2004 (2005), the humus content is estimated as very low (less than 1.1 %) and low (1.1-2.0 %) in a 0-30 cm layer of sod-medium-podzolic sandy loam soil according to the options of the experiment. On the Grishina-Orlov scale, the humus content is estimated as very low (less than 2%), which indicates a low potential fertility of the examined soils.

Analysing factor 2 (introduction into the soil, seed treatment and introduction of biopreparations during the growing season of potatoes), an increase in humus content was noted compared to the control option from 0.98 relative % on Option 6 (Treatment of tubers with Mycohelp – 2.0 L/t and three-time treatment with Mycohelp – 1.0 L/ha during the growing season) to 12.2% on Option 8 (application of Phytohelp for

tubers treatment at a dose of 1.0 L/t and three-time treatment with Phytohelp at a dose of 1.0 L/

ha by growing season) against the background without a destructor.

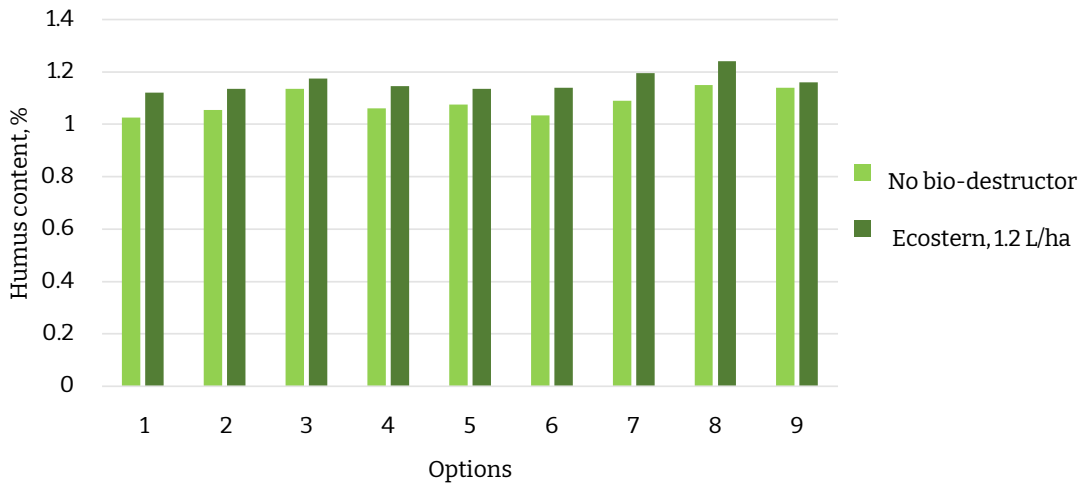


Figure 1. Humus content in a 0-30 cm layer of sod-medium-podzolic sandy loam soil in various options* of treatment of tubers and vegetative plants with biopreparations

Notes: 1. Without introducing biopreparations; 2. Application of 2.0 L/ha of Mycohelp and three-time treatment with Agate at 25-100 ml/ha; 3. Application of 2.0 L/ha of Mycohelp and three-time treatment with Regoplant – 50 ml/ha; 4. Application of 2.0 L/ha of Mycohelp and three-time treatment with Phytohelp – 1.0 L/ha; 5. Application of 2.0 L/ha of Mycohelp and three-time treatment with Stimpo – 15 ml/ha; 6. Treatment with Mycohelp – 2.0 L/t and three-time treatment with Mycohelp – 1.0 L/ha during the growing season; 7. Treatment of tubers with 50 ml/t of Regoplant and three-time treatment with 50 ml/ha of Regoplant; 8. Application of Phytohelp for processing tubers at a dose of 1.0 L/t and three-time treatment with Phytohelp at a dose of 1.0 L/ha during the growing season; 9. Treatment of tubers with Stimpo – 15, ml/t and three-time treatment with Stimpo at 15 ml/ha

Against the background of Ecostern application at a rate of 1.2 L/ha, an increase in humus content to the control option was also established from 1.34 relative % on option 2 (introduction of 2.0 L/ha of Mycohelp into the soil and three-time treatment during vegetation, Agate 25 – 100 mL/ha) to 10.71% on option 8 (use of Phytohelp for processing tubers at a dose of 1.0 L/t and three-time treatment with Phytohelp at a dose of 1.0 L/ha during vegetation). The best option was Option 8, where the relative increase in humus content was 12.2% against the background without a destructor. Against the background of Ecostern 1.2 L/ha, this option was also

the best, an increase of 10.8 relative % compared to the control option and 20.98% compared to the control without a destructor.

Figures 2 and 3 show the results of determining the mineral nitrogen content for the use of biopreparations in potato cultivation. According to the results of the study, it was established that the content of mineral nitrogen in the germination phase of the crop when applying the Ecostern destructor on average for factor 1 was lower by 2.09 mg/kg of soil compared to options that did not use the destructor. This phenomenon can be explained by the fact that microorganisms that were in the bio-destructor absorbed mineral nitrogen.

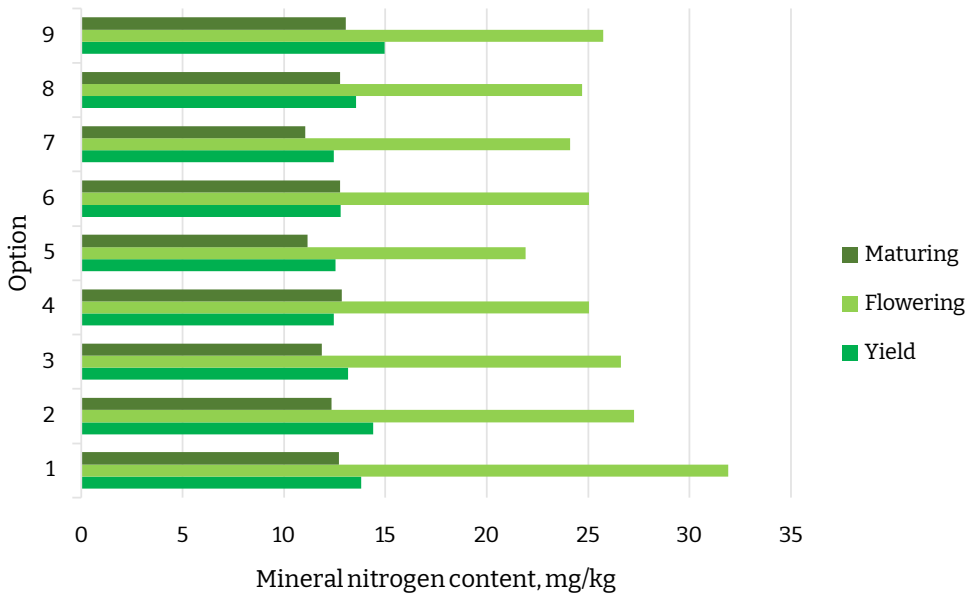


Figure 2. Dynamics of mineral nitrogen content 0-30 cm in the sod-medium-podzolic sandy loam soil layer under various options* of treatment of tubers and vegetative plants with biopreparations against a variant without a destructor

Notes: 1. Without introducing biopreparations; 2. Application of 2.0 L/ha of Mycohelp and three-time treatment with Agate at 25–100 ml/ha; 3. Application of 2.0 L/ha of Mycohelp and three-time treatment with Regoplant – 50 ml/ha; 4. Application of 2.0 L/ha of Mycohelp and three-time treatment with Phytohelp – 1.0 L/ha; 5. Application of 2.0 L/ha of Mycohelp and three-time treatment with Stimpo – 15 ml/ha; 6. Treatment with Mycohelp – 2.0 L/t and three-time treatment with Mycohelp – 1.0 L/ha during the growing season; 7. Treatment of tubers with 50 ml/t of Regoplant and three-time treatment with 50 ml/ha of Regoplant; 8. Use of Phytohelp for processing tubers at a dose of 1.0 L/ha and three-time treatment of Phytohelp at a dose of 1.0 L/ha during the growing season; 9. Treatment of tubers with Stimpo – 15, ml/t and three-time treatment with Stimpo at 15 ml/ha

At the beginning of the growing season, the amount of mineral nitrogen was at a low level, with the exception of options 2, 3, and 9 against the background without Ecostern and amounted to 13.95–18.8 mg/kg. During the flowering phase, the mineral nitrogen content increased to the average level of nitrogen supply in options 4, 5, and 8, where it amounted to 24.1; 23.1, and 23.4 mg/kg of soil against the background 1 and 24.05; 21.9, and 24.7 mg/kg against the background 2, respectively. In options 2, 3, 6, 7, and 9, the mineral nitrogen content was estimated to be increased both using a bio-destructor and the application of 1.2 L/ha of Ecostern.

The highest content was established on Option 2 (application of 2.0 L/ha of Mycohelp and three-time treatment with Agate 25 – 100 ml/ha) without stubble destructor – 30.2 mg/kg of soil, while with the destructor on this option, the content was 27.2 mg/kg. Slightly lower values were established in option 3 (application of 2.0 L/ha of Mycohelp and triple treatment with Regoplant – 50 ml/ha), where the values on backgrounds 1 and 2 were 26.8 and 26.6 mg/kg, respectively. In general, during the flowering stage, the changes in mineral nitrogen content were lower compared to the germination stage for treatments 6, 7, and 9.

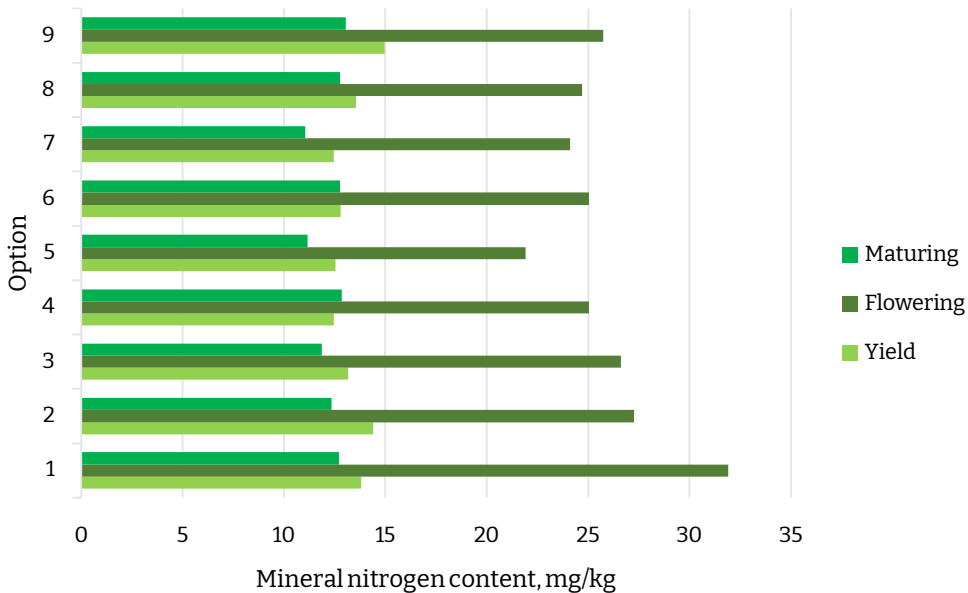


Figure 3. Dynamics of mineral nitrogen content 0-30 cm in the sod-medium-podzolic sandy loam soil layer under various options* of treatment of tubers and vegetative plants with biopreparations on the variant with the destructor *Ekostern* 1,2 L/ha

Notes: 1. Without introducing biopreparations; 2. Application of 2.0 L/ha of *Mycohelp* and three-time treatment with *Agate* at 25–100 ml/ha; 3. Application of 2.0 L/ha of *Mycohelp* and three-time treatment with *Regoplant* – 50 ml/ha; 4. Application of 2.0 L/ha of *Mycohelp* and three-time treatment with *Phytohelp* – 1.0 L/ha; 5. Application of 2.0 L/ha of *Mycohelp* and three-time treatment with *Stimpo* – 15 ml/ha; 6. Treatment with *Mycohelp* – 2.0 L/t and three-time treatment with *Mycohelp* – 1.0 L/ha during the growing season; 7. Treatment of tubers with 50 ml/t of *Regoplant* and three-time treatment with 50 ml/ha of *Regoplant*; 8. The use of *Phytohelp* for processing tubers at a dose of 1.0 L/t and three-time treatment of *Phytohelp* at a dose of 1.0 L/ha during the growing season. 9. Treatment of tubers with *Stimpo* – 15, ml/t and three-time treatment with *Stimpo* at 15 ml/ha

At the end of the vegetation period, during the maturity phase, the amount of mineral nitrogen decreased and was at a low level on two fertiliser backgrounds except for option 2 (application of *MikoHelp* at 2.0 L/ha and three treatments of *Agat* 25 at 100 ml/ha during vegetation). On the background without *Ekostern*, it was at an average level, but the yield was lower compared to the background where *Ekostern* was applied at 1.2 L/ha.

The main purpose of using biopreparations for growing crops is to ensure their high and stable productivity. The bio-preparations had an impact on the potato tuber yield in the

loamy-sandy soil, as shown in Table 1. Analysing the results of the conducted study, despite the actions of predecessors and types and methods of application of biopreparations, the weather conditions caused a negative impact on the potato yield.

On average, the potato yield for all options without bio-destructors was in the range of 12.4–13.8 t/ha with an increase of 1.8 to 3.3 t/ha compared to the control. The highest productivity was obtained when treating tubers before planting with *Mycohelp* at a dose of 2.0 L/t and *Regoplant* biopreparation at a dose of 50 ml/t, *Phytohelp* at a dose of 1.0 L/t, and *Stimpo* – 15 ml/t

with their triple application to vegetative plants. The highest yield (13.8 t/ha) was obtained using Phytohelp, slightly lower – 13.7 using Stimpo, Regoplant – 13.5 t/ha, and MycoHelp – 13.1 t/ha.

Table 1. The potato yield under the application of biopreparations in the study at the Volyn State Agricultural Research Station of the Institute of Potato Cultivation of the NAAS of Ukraine

A Factor	B Factor	Yield, t/ha	+/- to control, %
Background 1. Without bio-destructor	1. Control (without applying biopreparations)	10.5	–
	2. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during vegetation, Agate 25 – 100 ml/ha	12.4	1.9
	3. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during vegetation, Regoplant – 50 ml/ha	12.3	1.8
	4. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during vegetation, Phytohelp – 1.0 L/ha	12.7	2.2
	5. Application of Mycohelp 2.0 L/ha to the soil and three-time treatment during vegetation, Stimpo – 15 ml/ha	12.4	1.9
	6. Treatment of tubers with Mycohelp – 2.0 l/t and three-time treatment with Mycohelp – 1.0 L/ha during vegetation	13.1	2.6
	7. Treatment of tubers with Regoplant 50 ml/t and three-time treatment with Regoplant 50 ml/ha during vegetation	13.5	3.0
	8. Application of Phytohelp for treating tubers at a dose of 1.0 L/t and three-time treatment with Phytohelp at a dose of 1.0 L/ha during vegetation	13.8	3.3
	9. Treatment of tubers with Stimpo – 15 ml/t and three-time treatment with Stimpo 15 ml/ha during vegetation	13.7	2.8
Background 2. Ekostern at 1.2 L/ha.	1. Control (without applying biopreparations)	11.4	-
	2. Application of Mycohelp 2.0 L/ha to the soil and three-time treatment during vegetation, Agate 25 – 100 ml/ha	13.0	1.6
	3. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during vegetation, Regoplant – 50 ml/ha	13.3	1.9
	4. Application of 2.0 L/ha of Mycohelp to the soil and three-time treatment during vegetation, Phytohelp – 1.0 L/ha	13.8	2.4
	5. Application of Mycohelp 2.0 L/ha to the soil and three-time treatment during vegetation, Stimpo – 15 ml/ha	12.9	1.5
	6. Treatment of tubers with Mycohelp – 2.0 l/t and three-time treatment with Mycohelp – 1.0 L/ha during vegetation	14.1	2.7
	7. Treatment of tubers with Regoplant 50 ml/t and three-time treatment with Regoplant 50 ml/ha during vegetation	14.2	2.8
	8. Application of Phytohelp for treating tubers at a dose of 1.0 L/t and three-time treatment with Phytohelp at a dose of 1.0 L/ha during vegetation	15.0	3.6
	9. Treatment of tubers with Stimpo – 15 ml/t and three-time treatment with Stimpo 15 ml/ha during vegetation	14.5	3.1
HIP ₀₅	A Factor	0.25	
	B Factor	0.54	
	AB	0.76	

Analysing the yield results of using Ecostern (1.2 L/ha), an identical relationship was established with the data obtained without using Ecostern. The highest productivity was

provided by Phytohelp, Regoplant, Mycohelp, and Stimpo preparations with their combined use – treatment of tubers before planting and three-time application on vegetative plants. The

yield increase for these preparations was in the range of 2.7-3.6 t/ha. The yield in options with the application of Mycohelp to the soil – 2.0 L/ha and the use of the above-mentioned biopreparations was 10.4-22.2 percent lower.

The introduction of Ecostern bio-destructor had a greater effect on the humus content compared to the options of using biopreparations for processing potato tubers and biopreparations for vegetative plants. Thus, in the options without the use of bio-destructors, the humus content was 1.025-1.15%, and with the use of Ecostern at a dose of 1.2 L/ha – 1.135-1.24% in the soil layer of 0-30 cm. On average, on the background with the Ekostern destructor at a rate of 1.2 L/ha, there was an increase in humus content by 0.08% compared to the background without the destructor. The improvement in humification conditions due to the application of the Ecostern can be explained by the better decomposition of the cover crop. A. Kovalenko *et al.* (2020) indicate that under conditions of sufficient moisture supply, the use of destructors increases the degree of decomposition of plant residues by 2.2-2.6 times compared to the control.

The use of Mycohelp (option 8) and Phytohelp (option 9) for processing tubers and three-time processing of potato plants during vegetation created the most optimal conditions for humification without using stubble bio-destructors. When using a stubble bio-destructor, the highest humus content (1.24%) was also observed in option 8 using the drug Fitohelp.

Researchers emphasise the role of microorganisms in the accumulation and transformation of nitrogen, as well as in the decomposition of plant residues used as organic fertilisers (Markovska *et al.*, 2020). They also have a positive impact on plant health (Solomiychuk & Pikoivskyi, 2021).

The decrease in mineral nitrogen content in the soil was also observed during the flowering

and maturation stages, with reductions of 0.67 mg/kg and 0.6 mg/kg, respectively. However, this is attributed to the better assimilation of mineral nitrogen by potato plants, which is reflected in the increased crop yield. O.V. Humenyuk (2013) established that the use of the straw destructor Filazonite MC for the decomposition of straw, in combination with $N_{120}P_{100}K_{160}$, resulted in higher mineral nitrogen content compared to the variant without the use of the straw destructor. This was observed in the dark grey forest soil.

Analysing the dynamics of mineral nitrogen content in the loamy-sandy soil, it is worth noting a considerable increase in the indicators during the flowering phase and a gradual decrease towards the end of the vegetation period. In the studies conducted on dark-grey forest soil, the content of both ammonium and nitrate nitrogen gradually decreased during the growth of table potatoes from the budding phase to the harvest (Humenyuk, 2013). Vaitkevičiene *et al.* (2019) found that statistically substantial amounts of mobile phosphates, potassium exchange, and mineral nitrogen in the soil during the potato growing season were established two weeks after applying BD 500 to the soil before planting potatoes. They observed that spraying the soil with BD 500 caused an increase in the activity of enzymes such as urease and sucrose.

In the control options on two backgrounds (without Ecostern and with Ecostern) in the flowering and ripening phase, the content of mineral nitrogen among the options was the highest, which is explained by slow potato growth and weak assimilation of this element by plants, while against the background with Ecostern (1.2 L/ha) the nitrogen content was slightly lower, which is explained by its better assimilation by potato plants and increased crop yield. Previous studies have shown that the

use of Ekostern as a cover crop created conditions for increasing the availability of nutrients for table potatoes, as indicated by the values of the oligotrophy coefficient less than 1 (Khomeenko *et al.*, 2022).

V.V. Dudchenko *et al.* (2020) established a high economic efficiency of using Ecosteron bio-destructor at a dose of 1 L/ha together with urea at a dose of 30 kg/ha, where the level of profitability for soybean cultivation was 254.6%.

The use of biopreparations without bio-destructors (background 1) and with Ecosteron at a dose of 1.2 L/ha (background 2) led to substantial increases in potato yield. On background 1, the yield ranged from 10.5 to 13.7 tonnes per hectare, with yield increments relative to the control ranging from 1.9 to 3.3 tonnes per hectare. On background 2, the yield of potato tubers ranged from 11.4 to 15 tonnes per hectare, with yield increments ranging from 0.5 to 1.2 tonnes per hectare. That is, a greater difference between the variants was observed on background 1, but the yield values were higher when using the bio-destructor Ekostern at a dose of 1.2 L/ha on the cover crop. The positive effect of biopreparations on potato growth and development can be explained by a decrease in potato damage by various diseases. According to Gleń-Karolczyk *et al.* (2022), the use of biopreparations led to a decrease in the average severity index of common scab, black scurf, and silver scurf in potato crops over three growing seasons. Therefore, they emphasise the important economic effect that is achieved by using biopreparations. Additionally, a negative correlation has been found between the overall average disease severity index and potato tuber yield.

Researchers from Egypt (Abbas *et al.*, 2014) found that both the vegetative biomass and potato tuber yield increased after treatment with rhizobacterial preparations. They investigated Biofertile biopreparation and indicated that on

most varieties, it provided approximately 50% coverage of the plants' nitrogen requirements. They observed that the yield of plants treated with 100% required nitrogen was similar to the yield obtained by applying Biofertile biopreparation at 50% of the required nitrogen level. Therewith, the dependence of inoculation on the potato variety was noted. Biopreparations were introduced by soaking potato tubers and spraying vegetative plants. Similarly, biopreparations were used during studies. As for another biopreparation that was used (Biocontrol), it provided protection for potato plants from pathogens and substantially increased the yield of potato tubers. In this study, the use of both fertilisers contributed to an increase in the yield of potato tubers by 25% compared to the control.

The papers of researchers from different countries are devoted to investigating the influence of biopreparations on potato productivity. However, the spectrum of biological preparations is vast, just like their applications, so it is important to examine the effectiveness of the specific biopreparations available in a particular region and evaluate their performance under local conditions to understand how these products can effectively contribute to agricultural practices in that specific area. Where they will find the most application, particularly on crops that are widely cultivated and in high demand. That is why the authors investigated the effectiveness of a whole range of biopreparations under the conditions of the Polissya region in Ukraine, focusing on the most common soil type in this zone, loamy-podzolic soils, and the cultivation of the most widely grown crop – potatoes. Analysing the options with different biopreparations for seed treatment and foliar spraying on growing plants, it is worth highlighting option 8, Phytohelp at a rate of 1 L/ha for potato seed treatment, followed by three additional foliar applications of the same biopreparation at a rate of 1 L/ha.

This option resulted in a yield of 13.8 t/ha in background 1 and 15 t/ha in background 2. Thus, in the conditions of Polissya region of Ukraine, it is recommended to use Phytohelp for treating potato tubers before planting and during vegetation, along with Ekostern bio-destructor in the cultivation of cover crops to preserve and restore the organic matter content, and increase the productivity of table potatoes on loamy-podzolic soils. Ultimately, one of the principles of organic production is the maximum preservation and restoration of agroecocenoses.

Thus, biopreparations that were used both for treating tubers and vegetative potato plants had a substantial impact on the content of humus, mineral nitrogen, and potato tuber yield in the loamy-sandy soil.

CONCLUSIONS

This study, conducted at the Volyn State Agricultural Research Station of the Institute of Potato Cultivation of the NAAS of Ukraine, found a positive effect of biopreparations on humus status and nitrogen content indicators was established on loamy-sandy soil. It was established that when cultivating white mustard as a cover crop, the application of the bio-destructor Ekostern creates better conditions for humification and ensures an increase in humus content in the 0-30 cm layer of loamy-sandy soil by 7.82-10.7 relative percentages. These results allow recommending the use of this preparation to accelerate the decomposition of cover crop biomass and preserve soil organic matter, which has significant agroecological importance. This is particularly important for organic potato cultivation

techniques. It was also observed that the mineral nitrogen content in the loamy-sandy soil during the emergence stage was higher by 0.15-4.4 mg/kg in variant 1 without the cover crop destructor compared to variant 2 with the application of Ekostern at a rate of 1.2 litres/hectare on the cover crop. During the flowering phase, the difference between backgrounds 1 and 2 was less pronounced. In option 2, the application of 2.0 L/ha of Mycohelp and three-time treatment with Agate 25-100 ml/ha had the highest values of mineral nitrogen content during the growing season of table potatoes. The use of biopreparations had a substantial impact on potato tuber yield in the loamy-sandy soil. The use of biopreparations for the treatment of tubers and vegetative plants had a greater impact on potato yield compared to the use of a stubble destructor. The best conditions for crop formation were option 8 using Phytohelp for processing tubers at a dose of 1.0 L/t and three-time treatment with Phytohelp at a dose of 1.0 L/ha during the vegetation stage resulted in a yield of 13.8 tonnes per hectare without the destructor and 14.5 tonnes per hectare with the cover crop destructor. Gains from the use of the destructor amounted to 0.5-1.2 t/ha. Studies on the influence of biopreparations on the reaction indicators of the soil environment and the composition of soil cations are considered promising.

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None.

CONFLICT OF INTERESTS

None.

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<https://orcid.org/0000-0002-5052-9223>**Вміст гумусу та азоту дерново-підзолистого ґрунту під впливом біопрепаратів за вирощування картоплі**

Анотація. В органічних технологіях вирощування картоплі використовують різні біо препарати, які зумовлюють суттєвий вплив як на ріст та розвиток культур, так і на показники родючості ґрунтів, що особливо важливо для дерново-підзолистих ґрунтів, які характеризуються низькою потенційною родючістю. Метою досліджень було встановлення змін вмісту гумусу та мінерального азоту дерново-середньопідзолистого ґрунту під впливом біопрепаратів для деструкції сидерату гірчиці білої та для обробки бульб і вегетуючих рослин картоплі. У двохфакторному досліді вивчали Фон 1: контроль без деструктора і деструктор Екостерн у дозі 1,2 л/га та Фон 2: дев'ять варіантів застосування біопрепаратів Агат, Репоплант, Міколелп, Фітохелп і Стимпо. Зразки ґрунту відбирали із шару 0-30 см дерново-середньопідзолистого супіщаного ґрунту на водно-льодовикових відкладах. У них визначали вміст загального гумусу за методом Тюріна, вміст мінерального азоту розраховували як суму амонійного та нітратного азоту, визначених потенціометрично. Внесення деструктора по зеленій масі сидерату сприяло підвищенню вмісту гумусу у 0-30 см шарі ґрунту, де він складав 1,135-1,24 % проти 1,025-1,15 % на варіантах без застосування біодеструктора. За вмістом мінерального азоту відмічено зворотну залежність, на варіантах із використанням деструктора Екостерн він був нижчим в середньому на 2,09 мг/кг ґрунту порівняно з варіантами, де не вносили деструктор. Найвищий вміст гумусу був на варіанті 8 (використання Фітохелп для обробки бульб у дозі 1,0 л/т і трьохкратна обробка Фітохелп у дозі 1,0 л/га по вегетації) – 1,15 на варіанті без деструктора і 1,24 % із застосуванням біодеструктора Екостерн, дещо поступався варіант 9 із біопрепаратом Фітохелп. Матеріали, викладені у статті можуть, мати практичну цінність для аграрних підприємств, що займаються вирощуванням органічної картоплі для забезпечення збереження та відтворення органічної речовини ґрунтів

Ключові слова: родючість; органічні технології вирощування; гуміфікація; мікроорганізми; деструктор; сидерати

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