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Oksana Tonkha
Doctor of Agricultural Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-0677-5494

Olga Pak *
Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0005-1282-5311

Volodymyr Kozak
PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0009-0635-9528

Oleg Hryshchenko
PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0001-7450-4389

Olena Pikovska
PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-5052-9223

Assessment of the influence of mineral fertilisers on the phosphate regime of meadow chernozem carbonate soil and yield of sunflower and winter wheat

Abstract. The relevance of the study lies in the need to maintain optimal levels of mobile phosphorus in carbonate soils to support healthy plant growth and development, as it can be converted into less mobile forms in such soils. The purpose of the study was to assess the impact of various long-term fertilisation strategies on the content of various forms of phosphorus in the soil to improve

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*Corresponding author

this availability. The research was conducted in 2019-2022 as a stationary experiment in a separate division of the National University of Life and Environmental Sciences of Ukraine "Agronomic Experimental Station" in Kyiv Oblast on meadow chernozem carbonate low-humus coarse-sawn light loamy soil in a five-field crop rotation, where the influence of different levels of fertiliser saturation (no fertiliser, minimum, average, and optimal) on soil phosphate status and yield of Etana winter wheat variety and Sumiko sunflower hybrid was investigated. Soil samples were taken from the 0-20 and 20-40 cm layers, and the group and fractional composition of phosphates was determined using the Chang-Jackson method and the content of mobile phosphates using the Chirikov and Machigin methods. According to the analysis of the group and fractional composition of soil phosphates, it was found that in meadow chernozem carbonate low-humus coarse-sawn light loamy soil, the content of iron phosphates prevails among all fractions during long-term fertilisation. The results showed an increase in the content of aluminium phosphates in the 0-20 cm surface layer of the soil of two variants with long-term fertilisation, and an increase in the content of the second fraction of soluble calcium phosphates ($Ca\text{-}P_{II}$), with the minimum saturation ($N_{27}P_{18}K_{20}$) with the highest available phosphate fraction for plants ($Ca\text{-}P_{I}$) is observed The content of mobile phosphates was maximal at optimal fertiliser saturation ($N_{81}P_{54}K_{62}$) and was 4.8 and 8.5 mg/100 g of soil, the aftereffect of organic fertilisers positively affected the accumulation of mobile phosphates in the soil. The highest yield of winter wheat (7.55 t/ha) and sunflower (4.28 t/ha) was obtained with optimal fertiliser saturation, the lowest – without the use of fertilisers, where it was 4.45 t/ha for winter wheat and 2.23 t/ha for sunflower. The results of the study can be used to develop more sustainable and effective strategies for using phosphorus in soils, which can help preserve soil resources and prevent possible contamination of water sources due to excessive phosphorus intake

Keywords: group and fractional composition; mobile phosphates; soil medium reaction; phosphate mobilisation; available phosphorus

INTRODUCTION

Soils by genetic types are characterised by a different composition of mineral forms of phosphates. Thus, di- and octacalcium phosphates predominate in carbonate soils, and calcium phosphates and fluorooxides (hydroxyl-, fluorapatite, variscite, etc.) predominate in slightly acidic soils, and aluminium and iron phosphates (variscite, strangite, barrandite, etc.) predominate in acidic soils. The stability of mineral compounds depends on different soil conditions. First of all, it depends on the size of the reaction of the soil environment, the activity of various cations (especially Ca, Mg, Al, Fe), and on fertilisers applied, liming, plastering, irrigation. Thus, A.O. Khristenko (2020) found that the systematic use of organo-mineral fertilisers creates conditions for increasing the mobility of phosphates even in conditions when the phosphorus balance was negative. Thus, they suggest that the use of even small fertiliser rates will create conditions for simple restoration of soil fertility. According to O. Litvinova *et al.* (2019; 2020), plants can use all those phosphorus fractions that are converted to phosphate ions in the soil. Phosphorus is the macronutrient of plant nutrition, without which their growth and development are impossible, which is why organic and mineral fertilisers are used to cover the removal of this element, and preserve and increase it in soils. S.L. Bauke *et al.* (2018) state that phosphorus levels in deep soil vary significantly depending on the specific feeding strategy used in long-term agricultural experiments. Long-term agricultural experiments show that the fertilisation methods used can significantly affect the availability of phosphorus in deep soil layers.

W.W. Zhang *et al.* (2019) proved that water-soluble fractions of P, the content of which in soils is only 0.8-8.0 mg kg^{-1}, are closely related to crop yields. In addition, plants absorb mobile, namely metabolically sorbed phosphorus compounds, which easily and quickly enter the soil solution. The content of mobile phosphates in non-fertilised soils varies significantly

(10-100 mg kg-1). F.J. van der Bom *et al.* (2019) found that fertiliser application methods and their forms are an important factor affecting P fractions in the soil. They described that the practice of long-term application of phosphorous fertilisers has a significant impact on the soil's ability to supply and retain phosphorus, changing its chemical characteristics over time. Understanding the impact of long-term application of phosphorous fertilisers is important for optimising soil management and ensuring sustainable phosphorus resources for growing crops. The study by Y.P. Wang *et al.* (2022) aims to create a global model for understanding the dynamics of inorganic phosphorus in soil, in particular, to investigate the relationship between the kinetics of metabolism and the bioavailability of phosphorus in soil, which affects various physical and chemical properties of soil. The paper examines how various soil characteristics, such as pH, texture, organic matter content, and mineral composition, affect the kinetics of inorganic phosphorus metabolism. This exchange process plays an important role in determining the availability of phosphorus for plants and its potential for release into the environment.

C.M. Nobile *et al.* (2020) investigated the sorption and availability of phosphorus in andosol after a decade of applying organic or mineral fertilisers, highlighting the importance of changes in soil pH and organic carbon compared to phosphorus accumulation. The study highlights how changes in soil pH and the presence of organic carbon that affect different fertilisation practices can affect the sorption and availability of phosphorus, affecting its availability for plant uptake. Understanding the interaction between soil pH, organic carbon content, and phosphorus accumulation is essential for optimising fertiliser nutrition strategies and managing phosphorus availability in agriculture and environmental systems, with important implications for sustainable nutrient management and environmental protection practices.

The results of the investigation of Ukrainian and foreign studies indicate that the processes of phosphate conversion in soil are complex and are associated with a number of phenomena: dissolution and precipitation, adsorption and desorption, mineralisation and biological absorption, and other processes of phosphorus conversion occurring in different soil, and climatic conditions with different intensity. Fertiliser application affects the available phosphorus concentrations in the soil in the long run. Therefore, the purpose of the study is to investigate the impact of various long-term fertilisation strategies on the availability of phosphorus in the soil to improve this availability.

MATERIALS AND METHODS

The research was conducted on the territory of a Separate Division of the National University of Life and Environmental Sciences of Ukraine (SD NUBiP of Ukraine) "Agronomic experimental station" (coordinates of the research site latitude: 50° 4'25.30"N, longitude: 30°13'18.14"E) in a stationary experiment in a five-field crop rotation with the following alternation of crops: clover – sunflower – winter wheat – grain corn – barley + clover in 2019-2022 PP. Table 1 shows various crop rotations and fertiliser compositions for growing sunflower and winter wheat in experimental plots used for research.

Table 1. Saturation of crop rotation with fertilisers in experimental plots

Crop rotation	Fertilisers for sunflower (NPK)	Fertilisers for winter wheat (NPK)
1. No fertilisers (control)	-	-
2. Minimal	$N_{27}P_{18}K_{20}$	$N_{25}P_{25}K_{35}$
3. Aftereffect of organic fertilisers	$N_{55}P_{36}K_{41}$	$N_{55}P_{55}K_{80}$
4. Average	$N_{55}P_{36}K_{41}$	$N_{90}P_{45}K_{45}$
5. Optimal	$N_{81}P_{54}K_{62}$	$N_{140}P_{70}K_{70}$

Source: compiled by the authors

The soil of the experimental site is meadow chernozem carbonate low-humus coarse-sawn light loamy, which has a slightly alkaline reaction of the soil solution in a layer of 0-20 cm (pH was 7.8) and a high absorption capacity of 31.2 meq/100 g of soil. Studies on the determination of the group and fractional composition of soil mineral phosphates by the Chang-Jackson method in the Ginzburg-Lebedeva modification in 0-20 and 20-40 cm layers (DSTU 7854:2015, 2015). This method is based on sequential tillage with various solvents, each of which extracts certain fractions of soil phosphates: the phosphorus fraction Ca-P_I, Ca-P_{II}, Ca-P_{III}, Al-P, and Fe-P. First, the fraction of the most soluble forms of phosphates of alkaline and alkaline earth elements (Ca-P_I fraction) was isolated using an ammonium-molybdate extract (pH 4.8): alkali metal and ammonium phosphates, acidic and freshly deposited Ca and Mg phosphates, and partially F^{2+} (like vivianite) phosphates pass into the extract. The second fraction of less soluble forms of phosphates (Ca-P_{II}) was determined in an acetate-molybdate extract (pH 4.3), where di-base and Mg phosphates (mainly secondary-formed di-, tri-, octacalcium phosphates) and a significant amount of F^{2+} (like vivianite) phosphates pass. The third fraction of phosphates (Al-P) was determined in a fluoramonic extract (pH 8.5), into which aluminium phosphates (such as variscite, wawelite, etc.) and part of organic phosphorus pass. The fourth fraction of iron-bound phosphates (Fe-P) was determined in the alkaline extract of the washed soil residue after preliminary extraction. Determination of the last fraction in the sequential isolation of mineral forms of phosphorus (Ca-P_{III}) was carried out in an acid extract (0.5 rate H_2SO_4), where highly basic calcium phosphates such as apatite (natural and secondary formed) pass. The content of mobile phosphates in non–carbonate soil samples was determined by Chirikov methods (DSTU 4115-2002, 2002), and in carbonate samples – by Machigin method (DSTU 4114-2002, 2002). Soil samples at the experimental sites were taken in 0-20 and 20-40 cm layers. The content of mobile phosphates was determined by Chirikov (DSTU 4115-2002, 2002) and Machigin (DSTU 4114-2002, 2002) methods. The study complied with the provisions of the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

Phosphorus, unlike nitrogen and potassium, does not disappear from the soil due to its inertness and accumulates in large quantities. This leads to a change in the phosphate regime of the soil: the ratio between different groups of phosphorous compounds, the degree of their mobility, and the redistribution of phosphorus forms along the soil profile.

It is important to note that most of the reserves of available phosphorus compounds are located in the arable soil layer and naturally in deeper soil layers they decrease. According to the analysis of forms of mineral phosphorus compounds in meadow chernozem carbonate low-humus coarse-sawn light loamy soil with the annual application of various fertiliser options, the predominant fraction in all variants of the experiment is iron phosphates (Table 2).

Table 2. Group and fractional composition of soil mineral phosphates according to the Chang-Jackson method in the Ginzburg-Lebedeva modification (2019-2022)

Fertiliser saturation	Mineral phosphate fractions, mg/100 g of soil				
	Ca-P_I	Ca-P_{II}	Ca-P_{III}	Al-P	Fe-P
Without fertilisers (control)	4.42	6.63	13.9	7.70	31.8
Minimum ($N_{27}P_{18}K_{20}$)	13.8	12.5	16.2	14.6	35.4
Aftereffect of organic fertilisers + $N_{55}P_{36}K_{41}$	8.71	9.65	13.5	9.90	45.5
Average ($N_{55}P_{36}K_{41}$)	4.42	7.24	12.3	7.42	33.0
Optimal ($N_{81}P_{54}K_{62}$)	9.12	13.1	19.7	15.1	51.2

Source: compiled by the authors

A high amount of iron phosphates is also observed in the variant without fertilisation (control) – 31.80 mg/100 g of soil. The greatest changes in this phosphate fraction occurred at the optimal saturation of fertilisers with the application of mineral fertilisers at the rate $N_{81}P_{54}K_{62}$ and amounted to 51.2 mg/100 g of soil, which is 19.4 mg higher than the amount of Fe-P in the control variant. In addition, a fairly significant increase in iron phosphates compared to the control was observed in the variant with the aftereffect of organic fertilisers + $N_{55}P_{36}K_{41}$ – 45.5 mg/100 g of soil, or 13.7 mg more than the control variant. Changes in the content of iron phosphates in variants with the introduction of lower rates of mineral fertilisers ($N_{27}P_{18}K_{20}$) and $N_{55}P_{36}K_{41}$ without the aftereffect of organic fertilisers were not so significant and exceeded the amount of Fe-P in the control variant by 3.63 and 1.21 mg/100 g of soil, respectively.

Soils contain from amorphous to crystalline forms of Fe oxides, such as goethite, whose effect on the retention of inositol phosphates is well known. Contribution of other common crystalline Fe oxides, such as hematite, magnetite, and maggemite. These oxides exhibit different ability to retain and release phosphorus due to their specific surface properties and resistance to protons, organic acids, and complexing agents. Thus, the four crystalline iron oxides showed different ability to retain organic phosphorus in the form of myoinositol hexaphosphate depending on the surface properties and stability of complexes, affecting the degree of release, accumulation, and turnover in soils.

With long-term application of mineral fertilisers, the content of aluminium phosphates in the surface layer of the soil of 0-20 cm of two variants increased especially. Option with the application of $N_{27}P_{18}K_{20}$ was distinguished by an increase in the Al-P fraction by 6.87 mg/100 g of soil compared to the control variant. In the variant with the introduction of mineral fertilisers at the rate $N_{81}P_{54}K_{62}$, the changes in aluminium phosphate content were even greater – 15.1 mg/100 g of soil versus 7.70 mg/100 g of soil in the control. Minor changes in the content of aluminium phosphates occurred in the variant with the aftereffect of organic fertilisers and the introduction of $N_{55}P_{36}K_{41}$ – 9.90 mg/100 g of soil, that is, only 2.2 mg/100 g of soil is higher relative to the Al-P content in the non-fertilised option.

In the variant with the introduction of only mineral fertilisers ($N_{55}P_{36}K_{41}$) conditions were created that contributed to minor changes in the amount of aluminium phosphates (7.42 mg/100 g of soil versus 7.70 mg/100 g of soil in the control). Under the influence of mineral fertilisers, the soil was enriched with active phosphorus mineral compounds. The amount of the second fraction of soluble calcium phosphates ($Ca\text{-}P_{II}$) increased most significantly in comparison with the control in variants with the rates of mineral fertilisers $N_{27}P_{18}K_{20}$ and $N_{81}P_{54}K_{62}$. Thus, the content of active phosphorus compounds in the control variant was at the level of 6.63 mg/100 g, while in the above-mentioned variants, this indicator increased, respectively, to 12.45 and 13.08 mg/100 g of soil. In the soil on variants with an aftereffect of organics + $N_{55}P_{36}K_{41}$ and by applying only mineral fertilisers ($N_{55}P_{36}K_{41}$), the increase in active mineral phosphorus compounds compared to the control was significantly less – by 3.02 and 0.61 mg/100 g of soil, respectively.

Content of the most accessible phosphorus fraction for plants ($Ca\text{-}P_{I}$) is observed in the variant with the introduction of $N_{27}P_{18}K_{20}$ – 13.8 mg/100 g of soil, and the least (4.42 mg/100 g of soil) – in the control variant and in the option with the application of mineral fertilisers at the rate $N_{55}P_{36}K_{41}$. By the content of strongly bound calcium phosphates ($Ca\text{-}P_{III}$ fraction) compared to the control variant, the options with the introduction of mineral fertilisers at the rate $N_{27}P_{18}K_{41}$ and $N_{81}P_{54}K_{62}$ are very different. In the 0-20 cm soil layer of the control variant, the amount of strongly bound phosphates was 13.92 mg/100 g of soil. In the variant with the addition of $N_{27}P_{18}K_{41}$, the content of this fraction increased to 16.19 mg/100 g of soil, which is 2.27 mg/100 g more than in the control. The use of a higher rate of mineral fertilisers contributed to an increase in the $Ca\text{-}P_{III}$ fraction to 19.72 mg/100 g of soil, which is 5.80 mg/100 g more than in the control version. Application of only mineral fertilisers at the rate $N_{55}P_{36}K_{41}$ and their application against the background of the aftereffect of organic fertilisers did not contribute to such a significant increase in the content of strongly bound calcium phosphates relative to the control variant. On the contrary, the content of the Ca-P_{III} fraction in the soil, these variants were lower compared to the control and amounted to 13.50 mg/100 g of soil in the variant with an aftereffect of organic fertilisers and 12.16 mg/100 g of soil in the version with the introduction of only mineral fertilisers.

One of the conditions for obtaining high stable crop yields and preventing phosphorus losses from soils is rational management of phosphorus nutrition. The study by Q. Wang *et al.* (2022), which covered a period of more than 29 years, found that the application of mineral fertiliser in the amount of 36 t/ha on chernozem provided higher yields of agricultural crops, and the level of phosphorus compounds compared to non-fertilised variants. However, there was practically no difference in crop yields when using nitrogen-potash and nitrogen-phosphorus-potash fertilisers. A possible reason for this is that adding nitrogen and potassium can increase plant phosphorus uptake and root biomass. L.P. Yuan *et al.* (2020) suggest that another reason for the lack of changes in crop yields is the rather high phosphorus content in soils. Most crops, especially grain crops, use only mobile forms of phosphorus. It is such crops as rye, wheat, barley and corn that have a very low degree of assimilation of hard-to-dissolve soil phosphorus compounds. This is the reason for a good response to the application of available forms of phosphorous fertilisers. Under these conditions, phosphorus is absorbed more vigorously and calcium is absorbed significantly less. If an excessive amount of calcium cations is formed, they bind phosphorus and transfer it to hard-to-reach forms. It is precisely because of the low availability of phosphorus available to plants in the soil that the payback of phosphorous fertilisers is quite high. The availability of phosphorus compounds in the soil is closely related to the reaction of the soil environment. The studies, conducted on meadow chernozem soil, found that the response of the soil environment varied depending on fertiliser (Fig. 1).

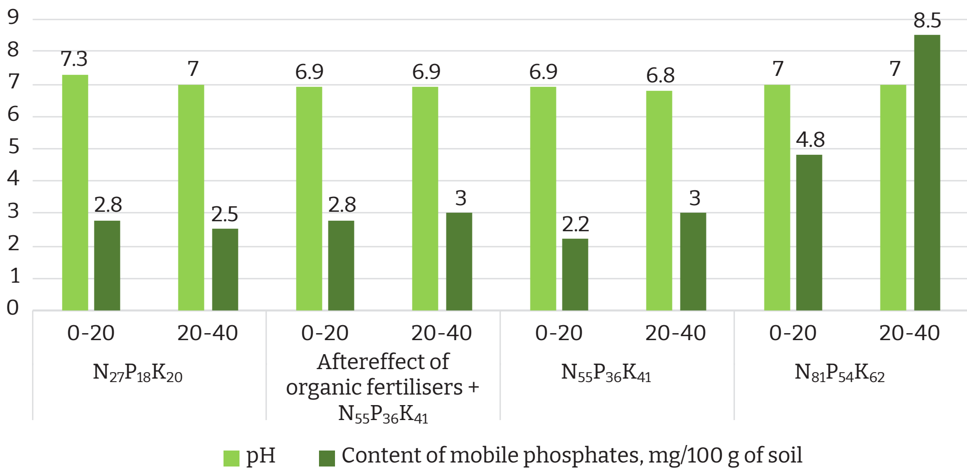

Figure 1. Reaction of the soil medium and the content of mobile phosphates according to the Machigin method in meadow chernozem carbonate soil (2019-2022)
Source: compiled by the authors

The control showed the lowest pH values – 6.5 in the 0-20 cm layer of soil and 6.6 in the 20-40 cm layer. Therefore, in these samples, the content of mobile phosphates was determined according to the Chirikov method and it was 15.9 and 17.6 mg/100 g of soil, respectively, according to the soil layers, which corresponds to a high content (15.1-20.0 mg/100 g of soil). Other soil samples contained carbonates, so the content of mobile phosphates was determined according to the Machigin method. Fertilisation options differed in pH values, which was 6.9-7.3 pH units in a 0-20 cm layer and 6.8-7.0 in a 20-40 cm layer of meadow chernozem soil. The highest pH value, which corresponds to a slightly alkaline reaction of the soil medium, was 7.3 in the variant with $N_{27}P_{18}K_{20}$.

The content of mobile phosphates on fertilised variants was 2.2-4.8 mg/100 g of soil in the upper 0-20 cm layer and 2.5-8.5 mg/100 g of soil in a 20-40 cm layer. Naturally, the highest content of mobile phosphates in the arable and sub-arable layers was on the variant with the highest rate of mineral fertilisers $N_{81}P_{54}K_{62}$ and rated as high in 0-20 cm layer and very high in 20-40 cm layer. On the variant with an aftereffect of organic fertilisers + $N_{55}P_{36}K_{41}$, the content of mobile phosphates according to Machigin was 2.8-3.0 mg/100 g of soil, respectively. Such values indicate an average degree of soil availability. Based on the research, the effectiveness of organic fertilisers on the phosphorus regime of the soil was proved, as the content of mobile phosphates was slightly lower in the variant with $N_{55}P_{36}K_{41}$ and amounted to 2.2-30 mg/100 g of soil.

G.N. Hospodarenko *et al.* (2015) based on mathematical analysis of spring barley yield data, show that with low fertilisation rates ($N_{45}P_{45}K_{45}$), it is not possible to maintain it at a constant level, although it was higher compared to areas without fertilisers. In the variants of the experiment with high doses of fertilisers, a decrease in the average annual yield increase was noted over time. The researchers conclude that the nutrient regime of the soil is no longer a limiting factor in the development of the spring barley crop, and its increase is possible due to such factor as the variety (Table 3).

Table 3. Influence of fertiliser application on the yield of the Ethana winter wheat variety and the Sumiko sunflower hybrid on meadow chernozem carbonate soil

Fertiliser saturation	Grain yield, t/ha^{-1}	
	winter wheat	sunflower
Without fertilisers (control)	4.45 e	2.23 e
Minimum ($N_{27}P_{18}K_{20}$)	5.30 d	2.83 d
Aftereffect of organic fertilisers + $N_{55}P_{36}K_{41}$	6.15 c	3.42 b
Average ($N_{55}P_{36}K_{41}$)	6.67 b	3.17 c
Optimal ($N_{81}P_{54}K_{62}$)	7.55 a	4.28 a

Note: means in columns with the different letter are highly significantly different according to the Fisher's test ($P \leq 0.05$)
Source: compiled by the authors

Analysing the data in Table 3, it should be noted that the use of fertilisers on meadow chernozem carbonate soil had a significant effect on the yield of both winter wheat and sunflower. The yield increase was 0.85-3.1 (winter wheat); 0.60-2.05 t/ha^{-1} (sunflower). The highest yield of winter wheat is obtained with optimal fertiliser saturation – 7.55 t/ha^{-1}, and the smallest – without fertiliser application – 4.45 t/ha^{-1}. The difference between the minimum and average saturation was significant and the increase in yield for the latter was 1.37 t/ha^{-1}. When growing sunflower seeds, the average fertiliser saturation also had a greater impact on the yield compared to the minimum, the difference was +0.34 t/ha^{-1}. The highest yield of sunflower is obtained with optimal fertiliser saturation – 4.28 t/ha^{-1}, and the smallest – without fertiliser application – 2.23 t/ha^{-1}.

Other researchers have also conducted similar studies. For example, M. Chen & T.E. Graedel (2016) found that the introduction of superphosphate for 65 years caused a significant increase in the proportion of all mineral phosphate fractions in the soil, except for the calcium-bound fraction. However, no significant effect of superphosphate on the content of organic phosphorus compounds was observed. In the experiment, where manure was used as a fertiliser containing phosphorus in an equivalent amount to superphosphate, the proportion of easily accessible phosphorus mineral compounds in the soil increased compared to the use of mineral fertilisers.

Some long-term studies by J. Ahlgren *et. al.* (2013) showed that the combination of mineral fertilisers with organic fertilisers primarily affected the concentration of P in the soil. Phosphorous fertilisers can directly affect the concentration of phosphorus in the soil by ingesting both orthophosphates and organic phosphorus compounds (Abdala *et al.*, 2015; Barrow *et al.*, 2015).

According to the conclusions of the research team, the application of organic fertilisers increased the concentration of organic matter in the soil. This led to an increase in the desorption of mineral phosphorus compounds due to changes in the soil reaction, which led to an increase in the availability of phosphates in soils (Sharpley *et al.*, 2004). C.M. Nobile *et al.* (2020) found that with an increase in the pH value of the acidic soil environment, phosphorus desorption Fe_2O_3 s Al_2O_3 (or $Fe(OH)_3$ and $Al(OH)_3$ occurs, instead, phosphorus desorption in carbonate soils occurred with a decrease in the pH value of the soil medium.

J.K. Whalen & C. Chang (2001) considered the accumulation of phosphorus in treated soils due to constant annual applications of mounted manure from a large feeding cowshed over a long period. The study aims to understand how the long-term practice of adding manure from a feeding cowshed to agricultural soils affects the accumulation of phosphorus, which is important for crop growth but can also cause problems in the environment when it accumulates in excessive amounts. The availability of phosphate fractions in the soil also depends on the processes of interaction of soil organic matter with metal oxides. As a result of such processes, some of the phosphorus compounds bind and become less accessible to plants (Fink *et al.*, 2016; Kramer & Chadwick, 2018). Other studies have shown that changes in the composition of phosphate fractions are important for determining the effectiveness of various mineral fertilisers and help to better reveal the availability of phosphorus in soils (Mundus *et al.,* 2017). Only a few comprehensive quantitative studies have covered such research Another important factor affecting the mobilisation of nutrients is soil microorganisms. Due to the fact that available P is constantly supplied due to insufficient dissolution, desorption, and mineralisation of organic phosphorus, the level of available compounds depends on the specific soil and climatic conditions, the crop grown, and the date of soil sampling (Tiessen & Moir, 1993).

M.B. McGechan & D.R. Lewis (2002) found that studying the availability of phosphorus compounds is challenging because some of the phosphorus in fertilisers can be fixed by the soil. In those areas where phosphorous fertilisers were applied, the presence of mobile phosphates in the composition of soil colloids and/or bound to soil particles was noted. When applying phosphorous fertilisers, the content of mobile phosphates in the soil increases, the degree of their mobility and availability for plants increases. M. Kulhánek *et al.* (2007) showed a gradual increase in phosphorus concentrations when applying organic and mineral fertilisers. The absorption of phosphorus by barley plants ranged from 9 to 14.5 kg/ha, and an increase in the use of phosphorus led to an increase in the concentration of phosphorus in plants. The closest relationship was found for aqueous extracts and phosphorus uptake by plants when the coefficient of determination was 65%.

Thus, the issue of phosphorus in soils is extremely relevant and complex at the same time. There is no doubt about the role of phosphorus in shaping crop productivity, but in soils, a significant part of the phosphorus reserves cannot be used by plants, since they are in hard-to-reach forms. The conducted research revealed the impact of different levels of fertilisation on phosphate composition and yields.

CONCLUSIONS

Based on the conducted studies, the influence of long-term fertilisation on the indicators of the phosphorous regime of meadow chernozem soil was established. The group and fractional composition of mineral phosphates according to the Chang-Jackson method in the Ginzburg-Lebedeva modification showed that the largest proportion is occupied by phosphorus compounds that are bound to iron: their content was 31.8–51.19 mg/100 g of soil. An increase in mineral fertilisation rates led to an increase in Al-phosphates. Fraction content ($Ca\text{-}P_I$), which is most accessible to plants, is noted in variant $N_{27}P_{18}K_{20}$. Naturally, the highest content of mobile phosphates in the arable and sub-arable layers was at optimal fertiliser saturation (option with the highest rate of mineral fertilisers $N_{81}P_{54}K_{62}$) and rated as high and very high respectively. It was 4.8 and 8.5 mg/100 g of soil, respectively. The content of mobile phosphates and the fractional composition of phosphorus compounds depend on the reaction of the soil medium. The lowest pH values (6.5) of meadow chernozem soil were found in the control, where a high content of mobile phosphates was detected; on fertiliser variants, the values were 6.9–7.3 pH units in the arable layer. At the same time, it is difficult to distinguish the effect of the soil reaction from the action of fertilisers, so studies on the dependence of the phosphate regime on pH in different soil conditions with similar fertilisation options will be promising. The minimum, average, and optimal fertiliser saturation on meadow chernozem carbonate soil had a significant effect on the yield of both winter wheat (0.85-3.1 t/ha^{-1}), and sunflower (0.60-2.05 t/ha^{-1}).

Future studies may consider different types of fertilisers and their impact on the phosphorus regime and plant yield. Learning the optimal fertiliser combinations can be useful for maximising yields and efficient use of resources. Further studies may also focus on the investigation of various plant species that are grown on meadow chernozem carbonate soils. This will allow understanding how the effect of mineral fertilisers can differ for different crops.

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CONFLICT OF INTEREST

None.

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Оксана Леонідівна Тонха
Доктор сільськогосподарських наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-0677-5494
Ольга Валеріївна Пак
Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0005-1282-5311
Володимир Миколайович Козак
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0009-0635-9528
Олег Володимирович Грищенко
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0001-7450-4389
Олена Володимирівна Піковська
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-5052-9223

Оцінка впливу мінеральних добрив на фосфатний режим лучно-чорноземного карбонатного ґрунту та урожайність соняшнику і пшениці озимої

Анотація. Актуальність дослідження полягає в необхідності збереження оптимального рівня рухомого фосфору у карбонатних ґрунтах для підтримки здорового росту та розвитку рослин, оскільки саме в таких ґрунтах він може переходити у менш рухомі форми. Метою дослідження було оцінити вплив різних довгострокових стратегій внесення добрив на вміст різних форм фосфору в ґрунті для покращення цієї доступності. Дослідження проводили у 2019-2022 рр. у стаціонарному досліді у Відокремленому підрозділі Національного університету біоресурсів і природокористування України «Агрономічна дослідна станція» Київської області на лучно-чорноземному карбонатному малогумусному грубопилувато-легкосуглинковому ґрунті у п'ятипільній сівозміні, де вивчали вплив різних рівнів насиченості добривами (без добрив, мінімальний, середній і оптимальний) на показники фосфатного режиму ґрунту і урожайність пшениці озимої сорту Етана і соняшнику гібриду Суміко. Зразки ґрунту відбирали з шарів 0-20 і 20-40 см, у них визначали групово-фракційний склад фосфатів за методом Чанга-Джексона, вміст рухомих фосфатів за методами Чирикова та Мачигіна. Згідно з аналізом групово-фракційного складу фосфатів ґрунту встановлено, що у лучно-чорноземному карбонатному грубопилувато-легкосуглинковому ґрунті серед усіх фракцій переважає вміст фосфатів заліза за довготривалого внесення добрив. Результати досліджень показали збільшення вмісту фосфатів алюмінію у поверхневому шарі ґрунту 0-20 см двох варіантів за довготривалого внесення добрив, а також підвищення вмісту другої фракції розчинних фосфатів кальцію ($Ca\text{-}P_{II}$), у мінімальної насиченості ($N_{27}P_{18}K_{20}$) відмічено найбільше доступної фракції фосфатів для рослин ($Ca\text{-}P_{I}$). Уміст рухомих фосфатів був максимальним за оптимальної насиченості добривами ($N_{81}P_{54}K_{62}$) і складав 4.8 і 8.5 мг/100 г ґрунту, післядія органічних добрив позитивно впивала на накопичення рухомих фосфатів у ґрунті. Найбільша урожайність пшениці озимої (7,55 т/га) і соняшнику (4,28 т/га) отримана за оптимальної насиченості добривами, найменша без застосування добрив, де вона склала 4,45 т/га для пшениці озимої та 2,23 т/га у соняшника. Результати дослідження можуть бути використані для розробки більш стійких та ефективних стратегій використання фосфору в ґрунтах, що може сприяти збереженню ґрунтових ресурсів та запобіганню можливому забрудненню водних джерел внаслідок надмірного внесення фосфору

Ключові слова: групово-фракційний склад; рухомі фосфати; реакція ґрунтового середовища; мобілізація фосфатів; доступний фосфор