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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 + N<sub>12</sub> + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub>, 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 NH<sub>4</sub><sup>+</sup> - N and NO<sub>3</sub> - 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<sup>+</sup>/Na<sup>+</sup> 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<sup>-3</sup>%. 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  $\text{pH}_{\text{KCl}}$  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 +  $\text{N}_{12}$  + 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  $4.5 \times 20$  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.

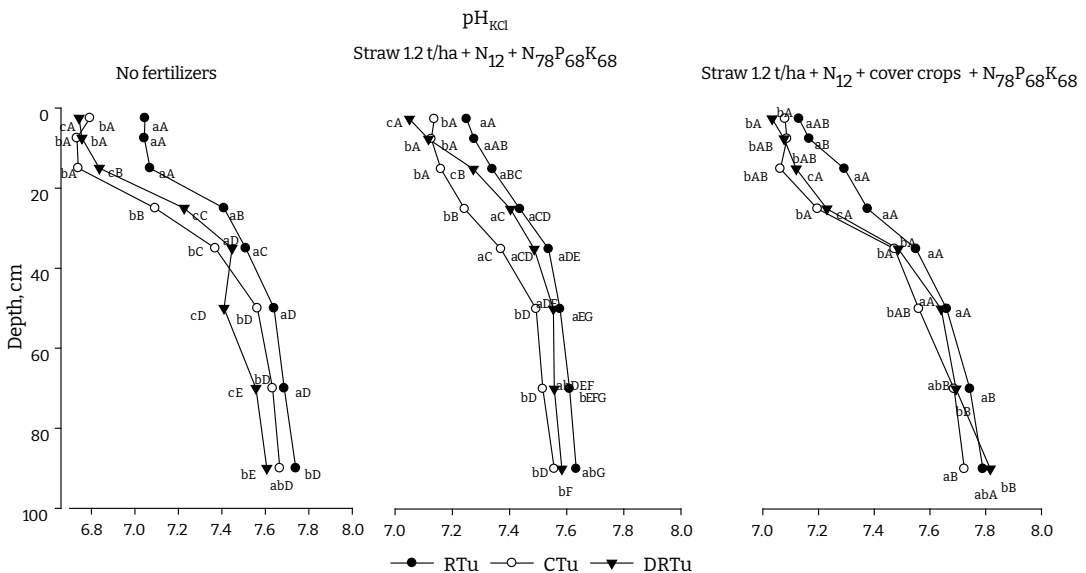
The arithmetic means of the results, significant differences, and the level of significance were determined using software such as Microsoft Excel 2016, IBM SPSS Statistics for Windows v. 20.0 (© SPSS, Chicago, Illinois), and SigmaPlot for Windows Version 14.0 (2017 Systat Software, Inc.). The average 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 +  $N_{12} + N_{78}P_{68}K_{68}$ ;

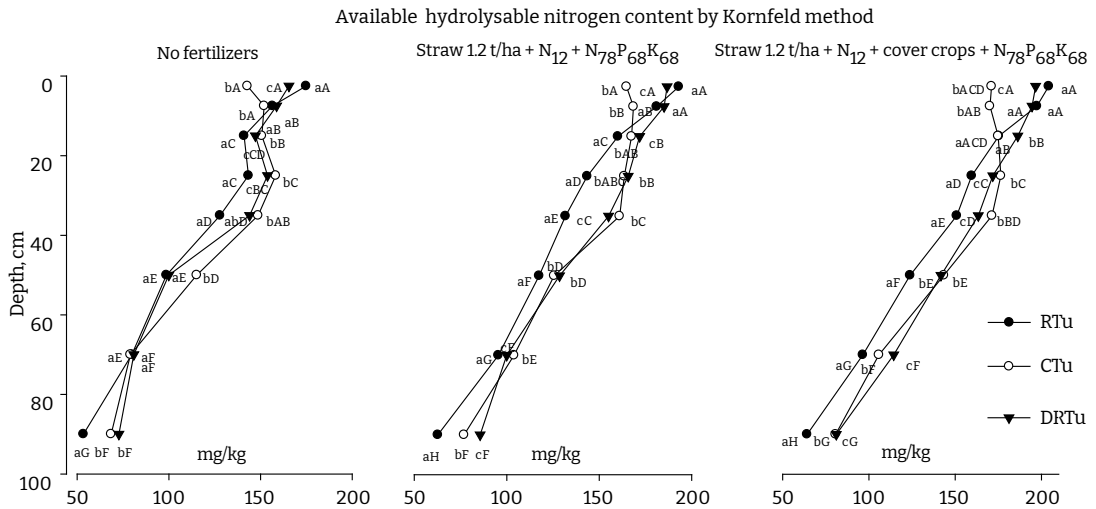
3) 7.13; 7.17; 7.29; 7.38; 7.55; 7.66; 7.74, and 7.79 – under RTu, 7.08; 7.09; 7.06; 7.20; 7.47; 7.56; 7.69, and 7.72 – under CTu, 7.03; 7.08; 7.12; 7.23; 7.49; 7.64; 7.69, and 7.82 – under DRTu with the addition of

straw 1.2 t/ha + N<sub>12</sub> + cover crops + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub>. On average for the 0-100 cm layer, the highest pH<sub>KCl</sub> 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 + N<sub>12</sub> + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub> 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 + N<sub>12</sub> + cover crops + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub>. A significant increase in pH<sub>KCl</sub> 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 + N<sub>12</sub> + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub> 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 CO<sub>2</sub> 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<sup>+</sup> and OH<sup>-</sup> 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 + N<sub>12</sub> + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub> and 0.1-0.6 and 0.1-0.2 – with the use of straw 1.2 t/ha + cover crops + N<sub>12</sub> + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub> accordingly. In more humid conditions created by the no-tillage soil management, denitrification processes are intensified, leading to the release of OH<sup>-</sup> 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<sub>KCl</sub> 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 + N<sub>12</sub> + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub>. 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<sub>KCl</sub> 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 N<sub>60</sub>, N<sub>120</sub>, and N<sub>240</sub> 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

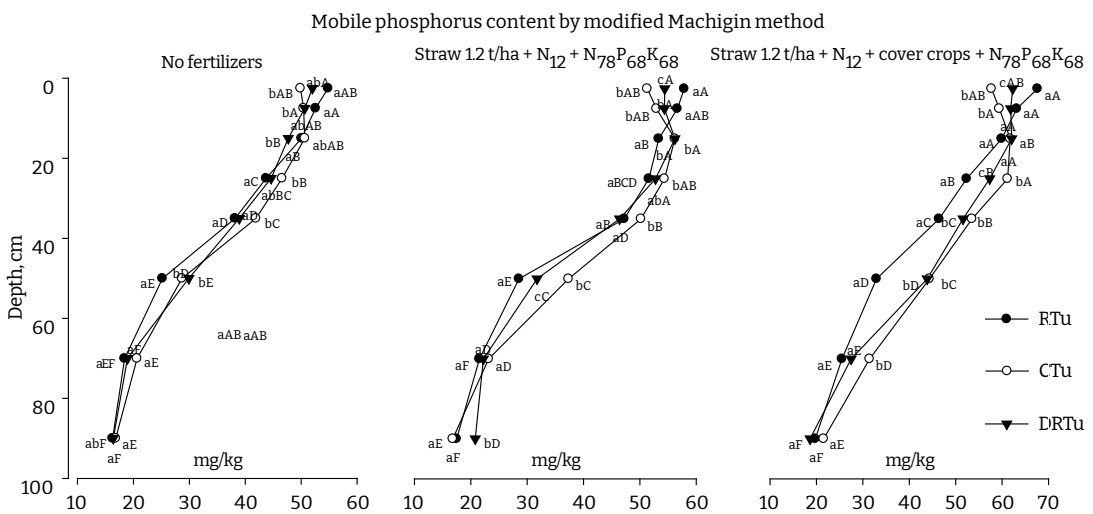
upper 0-10 cm layer of the typical chernozem soil during plowing, leading to a decrease in alkaline-soluble nitrogen compounds under this tillage practice. Therewith, this method of tillage accumulated more available hydrolysed nitrogen compounds in the layer of 20-40 cm – 153.43-173.91 mg/kg under CTu 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 CO<sub>2</sub> 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).

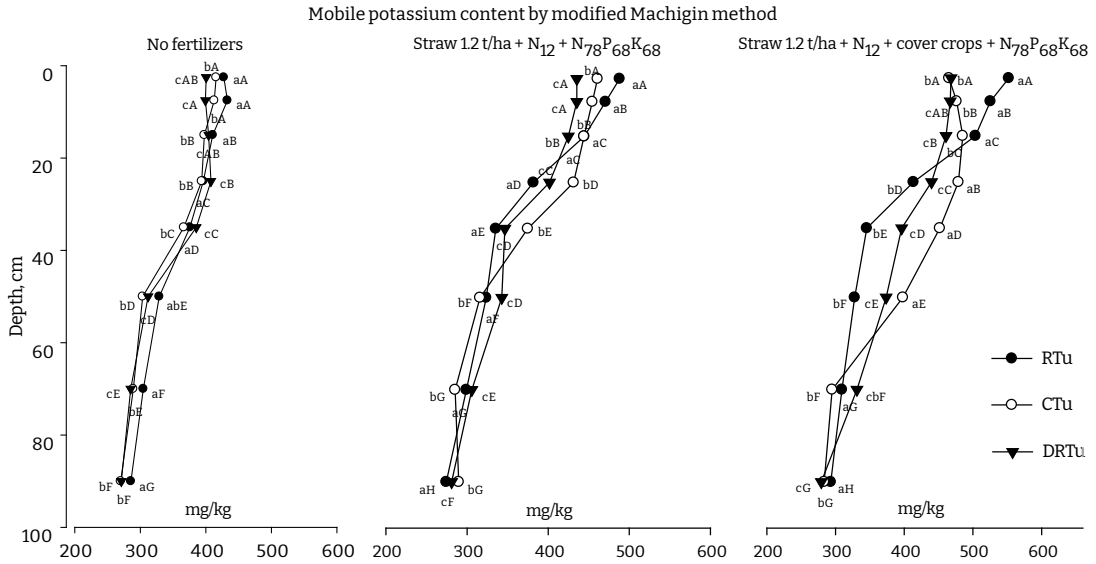


**Figure 3.** Profile changes in the content of mobile phosphorus compounds in typical chernozem for the use of shallow minimum tillage (RTu), plowing (CTu) and deep minimum tillage (DRTu)

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  $\text{CaCl}_2$  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)

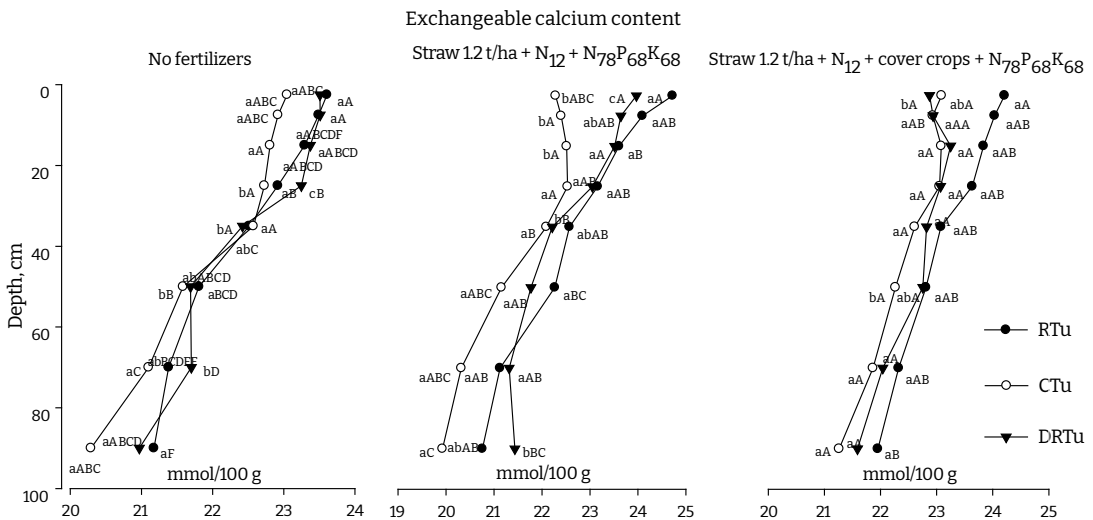
The lowest content of mobile potassium in the above-mentioned layer was noted for DRTu, the variant with CTu occupied an intermediate position. Under plowing, the content of exchange potassium was notably higher than other tillage technologies in a layer of 20-40 cm. The findings of Kumar *et al.* (2022) 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).



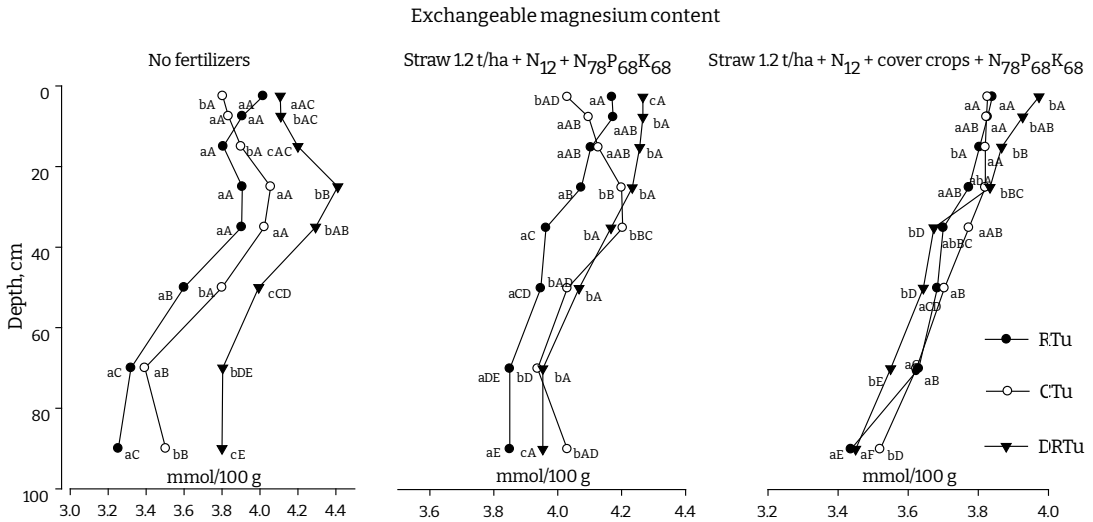
**Figure 5.** Profile changes in exchangeable calcium content in typical chernozem soil under the use of shallow minimum tillage (RTu), plowing (CTu) and deep minimum tillage (DRTu)

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).

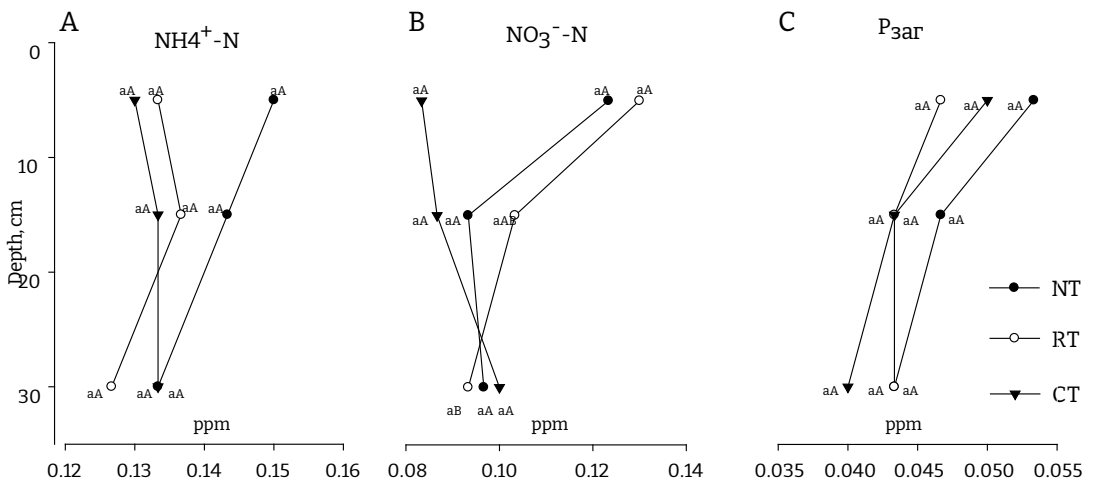
Stankowski *et al.* (2022) observed no significant difference in the impact of no-till, minimal tillage, and conventional tillage on the content of exchangeable magnesium in the lower layers of sandy loam brown soil in Pomerania. On the experimental plots where cover crops were used in combination with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

ha + N<sub>12</sub> + N<sub>78</sub>P<sub>68</sub>K<sub>68</sub>, 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 NH<sub>4</sub>-N (A) and NO<sub>3</sub>-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 NH<sub>4</sub>-N (0.15 ± 0.015 ppm), NO<sub>3</sub>-N (0.13 ± 0.015 ppm), and P<sub>total</sub> (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 + N<sub>12</sub> + N<sub>76</sub> P<sub>66</sub> K<sub>66</sub>, 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