UDC 631.361
DOI: 10.15587/1729-4061.2023.289238

IMPROVING THE QUALITY OF PROCESSING THE SOIL ENVIRONMENT BY DETERMINING THE RATIONAL STRUCTURAL AND TECHNOLOGICAL PARAMETERS FOR THE ROLLING WORKING BODIES

Igor Shevchenko
Doctor of Technical Sciences, Doctor of Agricultural Sciences, Professor, Corresponding Members of National Academy of Agrarian Sciences of Ukraine
Institute of Oilseed Crops of the Ukrainian Academy of Agricultural Sciences (IOC UAAS)
Instytutska str., 1, Soniachne vill., Ukraine, 69093

Gennadii Golub
Doctor of Technical Sciences, Professor
Department of Tractors, Cars and Bioenergy Resources*

Nataliya Tsyvenkova
Corresponding author
PhD, Associate Professor
Department of Tractors, Cars and Bioenergy Resources*
Department of Renewable Organic Energy Resources**
E-mail: nataliyatsyvenkova@gmail.com

Iryna Shevchenko
PhD, Associate Professor
Engineering Educational and Scientific Institute of Zaporizhzhia National University
Zhukovskoho str., 66, Zaporizhzhia, Ukraine, 69600

Vladyslav Shubenko
PhD, Associate Professor
Department of Mechanics and Agroecosystems Engineering***

Oleksandr Medvedskyi
PhD
Department of Agricultural Engineering and Technical Service***

Oleh Pluzhnikov
Assistant
Department of Mechanics and Agroecosystems Engineering***

Ivan Omarov
Postgraduate Student
Department of Renewable Organic Energy Resources**

*National University of Life and Environmental Sciences of Ukraine
Heroyiv Oborony str., 15, Kyiv, Ukraine, 03041
**Institute of Renewable Energy of the National Academy of Sciences of Ukraine
Hnata Khotkevycha str., 20-a, Kyiv, Ukraine, 02049
***Polissia National University
Staryi blvd., 7, Zhytomyr, Ukraine, 10008

The object of this study is the process of soil compaction with ring-spur and ring-tooth rollers. Based on the zonal optimization of the agrophysical parameters of the arable horizon, the influence of the rolling working bodies on the soil environment in terms of creating a uniform set layer density during pre-sowing tillage was investigated. It was established that soil density should be evaluated in a zonal section together with its aggregate composition, humus content, moisture, etc. Smooth-water-filled, ring-tooth, and ring-spur rollers were studied. The use of a smooth water-filled roller in previous studies contributed to the high unevenness of the compaction of the upper and lower layers of the arable horizon, which indicated the impracticality of further experiments. The research of ring-tooth and ring-spur rollers was carried out by the method of a multifactorial experiment under defined soil and climatic conditions (soil type, sod-podzolic; layer-by-layer soil moisture, 26...28 %; layer-by-layer soil density, 0.96...1.25 g/cm^3). Regression models were built of the influence of the specific load, the frequency of passes, and the working speed of the unit on the density of the soil in layers: 0–5; 5–10; 10–15; 15–20; 20–25; 25–30 cm. To assess the heterogeneity of soil density in layers 0–5 and 5–10 cm, a data array was constructed. It was established that the ring-spur roller, even at a speed of up to 6 km/h, is not a tool suitable for regulating the equilibrium density of the seed layer. The best for pre-sowing soil cultivation is a ring-tooth roller (specific soil load, 350 kg/m; unit speed up to 6 km/h).

The derived regression equations make it possible to select such a specific load on the ring-tooth roller that could provide a rational value of the layer density of the soil. This is economically and environmentally expedient

Keywords: layer-by-layer soil density, heterogeneity of soil density, ring-spur roller, ring-tooth roller

Received date 18.08.2023
Accepted date 20.10.2023
Published date 30.10.2023

How to Cite: *Shevchenko, I., Golub, G., Tsyvenkova, N., Shevchenko, I., Shubenko, V., Medvedskyi, O., Pluzhnikov, O., Omarov, I. (2023). Improving the quality of processing the soil environment by determining the rational structural and technological parameters for the rolling working bodies. Eastern-European Journal of Enterprise Technologies, 5 (1 (125)), 54–63. doi: https://doi.org/10.15587/1729-4061.2023.289238*

1. Introduction

Rolling is one of the basic tillage operations, owing to which crushing of large clods, destruction of the soil crust, compaction, and leveling of the field surface is ensured [1]. Providing a rational value of the layer density of the soil set, depending on the climatic conditions, allows maintaining optimal and uniform capillarity of the soil with a high content of soil moisture [2].

This contributes to better germination, stimulation of bushing, and creation of optimal conditions for plant growth and development. However, the above is achieved subject to condition of a correctly selected design of the tillage roller.

A particularly important role belongs to the density of the soil in the arable horizon under modern conditions of intensive growth of technogenic influence on the soil environment. It is necessary to study and forecast soil compaction within the framework of zonal and micro zonal technologies under specific soil and climatic conditions. As a result of excessive soil compaction and the development of erosion, there is a violation of the ecological balance of soil ecosystems and, as a result, an active loss of humus. Dehumification of arable soils has covered almost all agricultural regions of the globe and is becoming a global problem in crop production.

The modern market of agricultural machinery offers rollers, which mainly differ in grip width, weight, surface geometry, and set of working bodies. Also, depending on the grip width and working conditions, rollers are manufactured in trailed and semi-trailer versions. There are certain requirements for the conditions and quality of the roller's work, the observance of which will ensure the effective execution of the technological process with minimal expenditure of working time, fuel, and money. Therefore, farmers face the task of choosing the right tool, taking into account certain conditions and its functional purpose [3]. This substantiates the importance of scientific research into determining the influence of the parameters of rolling working bodies on the distribution of layer-by-layer density and soil heterogeneity [4, 5].

Today, a number of studies on determining the dependence of the layer density of the soil on the specific load on the pile are relevant [6, 7]. The weight, outer diameter, and shape of the working surface have the greatest influence on the efficiency of the roller. According to [8], the soil is compacted under the influence of the mass of the rollers, and the effort to roll them depends significantly on the size of the diameter. In practice, it has been established that with an increase in the diameter of the roller, less effort must be spent on rolling, although the quality of soil compaction will decrease. But in the case of a significant reduction in the diameter of the roller, its rolling over the field surface will deteriorate, which will lead to the collapse of the soil in front of the roller in the direction of movement of the unit, and as a result, to the destruction of its structure [9]. A roller with a small diameter will compact mainly the top layer, and a larger one will compact the soil more evenly throughout the entire depth. The type of roller is selected depending on the characteristics and properties of the soil [9].

These statements are based on experimental studies performed under different conditions for different types of soil and tillage rollers, which makes their universal application impossible. Therefore, the task of researching the influence of rolling working bodies on the differentiated distribution of soil density of the arable horizon remains relevant.

The results could make it possible to reduce the number and complexity of experimental studies, reduce time and investment in project works, and quantitatively evaluate the efficiency of rolling units during their operation on different types of soils.

2. Literature review and problem statement

According to [10], soil density is the most significant characteristic that determines its composition, water-physical properties, and biological activity. Water, air, heat, and nutritional modes of life of soil flora and fauna depend entirely on the density of the soil.

In studies [11, 12] it is noted that both high and low soil density are negative factors for growing agricultural crops. The high density of soils is the cause of disruption of air and gas exchange processes, increased content of unavailable moisture and a sharp reduction in the content of available moisture. Loose soil is not able to retain moisture and ensure contact between soil particles and seeds, and shrinkage is generally the cause of impaired development of the root system of plants.

Similar studies were conducted by the authors of work [13]. They investigated the effect of three types of tillage and three types of in-row compaction on the physical properties of the seed bed and the quality of crop germination on dry soil. In the first study, there was no compaction (U0), in the second and third – 60 kPa (U1) and 90 kPa (U2), respectively. Types of tillage: ordinary ZO (plough+disc harrow+soil float); abbreviated No. 1 CO1 (rotary cutter with a horizontal axis); abbreviated No. 2 CO2 (rotary cutter with a vertical axis with a roller). Treatment CO1 and degree of compaction U2 ensured the highest content and availability of moisture in the soil. The CO2 treatment and the degree of U2 compaction provided the highest values of cone indices and soil bulk density. The authors noted how best to combine the degree of soil compaction with a certain type of tillage in order to ensure the optimal time of emergence of seedlings. However, the study is limited by the types of soils for which the obtained results are adequate.

Therefore, according to [11–13], the full development of agricultural crops is possible under the condition of ensuring a certain specified value of soil density (the terminological definition is optimal soil density), which is achieved by appropriate mechanical processing. At the same time, different types of soils and, accordingly, agricultural crops have their specific determined value of optimal density. However, in the studies, the authors did not deeply investigate such a parameter as «optimal soil density», and the parameter of the mechanization of the tillage process was studied only on a small list of the corresponding mechanized tools.

The question of the mechanization of the soil tillage process, which ensures optimal soil density, and the formulation of the definition of this parameter are presented in works [14, 16]. It is compliance with the value of the optimal soil density that ensures the maximum possible yield indicators of plant crops.

According to [14], various methods of soil cultivation were studied in order to achieve the value of its optimal density, favorable for growing agricultural crops. Therefore, the main goal was to establish the influence of the parameters of the working bodies of the used equipment on the parameter of soil spalling, which was determined by the size of the particles. As a result of the complex and superimposed effects of field conditions, soil types, the structure of crops, and the type of tillage tools used, an array of data on the mass distribution of soil layers was obtained. The work is of significant practical importance as accurately predicting the influence of the soil treatment method on changes in the composition and distribution of soil layers through mathematical modeling is an incredibly difficult task. However, the paper considers only a few types of soils, mechanized means of soil cultivation and their modes of operation, which does not allow the obtained results to be generalized.

The dependence of soil bulk density on the depth of tillage, moisture content, and soil texture, type of drive system, number of passes, speed of movement, and pressure of tillage equipment and its working bodies on the soil is presented in [15]. It was established that increasing the traction of the tractor wheels had a significant effect on the increase in the degree of soil compaction, while increasing the speed of the tractor, on the contrary, decreased this parameter. In addition, an increase in soil moisture content led to an increase in the degree of soil compaction, and this phenomenon was intensified in clayey soils such as loam. The influence of the pressure of the running system on the soil, depending on the design parameters of the tractors, was also deeply studied in [16].

The results of [14, 15] can be applied in studying the influence of mechanized tillage tools on the differentiated distribution of soil density of the arable horizon.

In view of the above, the requirements for the cultivation of different soils differ. Therefore, a differentiated approach to the processes of mechanization of the main, surface and pre-sowing soil cultivation is needed: over-compacted soils should be loosened, and soils with close to optimal density should be subjected to only minimal impacts. This will reduce energy costs for soil preparation by 25...30 % [17].

A significant part of the world's land fund is occupied by sod-podzolic soils, the share of which is 350 million hectares. In Ukraine, the area of sod-podzolic soils is 2.5 million hectares and they are widespread, mainly in the north and in the northwestern part of Ukraine, in Polissia. In the available literature, there is a lack of information on the value of the optimal density for various crops on sod-podzolic soils, indicating the methods of achieving this density. According to the data of scientific work [18], the optimal density of sod-podzolic soils for the cultivation of cereals is 1.2...1.4 g/cm^3, and for gray forest soils – 1.2...1.3 g/cm^3. The density of the soil layer of 0...10 cm has the highest impact on the yield, which is probably due to the initial development of the root system in this layer under these conditions.

However, in order to argue about the real condition of soils, in addition to the average density of the arable horizon, such a parameter as the heterogeneity of the density of the soil layer should be considered. According to [19], high heterogeneity of soil density causes a decrease in yield compared to a uniform distribution of density. Crop losses caused by the inhomogeneity of the density distribution in the arable horizon at its optimal average density can be represented by a relationship that relates the degree of yield reduction to the empirical coefficient and the root mean square value of the soil density deviation. That is, an increase in the dispersion of density values will lead to a loss of yield.

Both above phenomena are described in work [20]. It states that the increase in the equilibrium density of the soil and the dispersion of the volumetric mass in the upper layer is a consequence of long-term intensive mechanical impact on the soil and, of course, the reason for a significant decrease in yield. The authors emphasize that the described phenomena are most characteristic of structureless, low-humus soils (soil-climatic zone of Polissia of Ukraine, turf-podzolic and forest soils), where the soil settles significantly from the moment of sowing to the emergence of seedlings.

In work [21], it is proposed to use rollers as independent tillage tools on low-humus soils. And they should be used both before and after sowing crops in order to ensure the final settlement of the soil, so as not to injure the root system of plants in the future. Failure to perform these operations, or their performance with low quality indicators, leads to significant crop losses.

According to [22, 23], rollers are a tool designed for rolling the soil. Conventionally, rollers can be divided into four types: smooth-water-filled, ring (ring-tooth and ring-spur), rod, spiral. Rollers differ in design features and the degree of impact on the soil and, therefore, have different purposes in the system of mechanized soil cultivation.

According to studies [24], ring rollers are the most widely used due to more intensive crushing of soil lumps compared to smooth ones. The best grinding is achieved when one section contains two rollers installed one behind the other and offset by half the distance between adjacent rings. The diameter of the rings ranges from 300 to 900 mm, and the specific load is 200...600 kg/m.

In turn, the authors of work [25] note that in arid and semi-arid regions, it is better to use a combined tillage tool (CTT) for compacting the seed layer. The combined tool combined a single-row chisel plow, a single-row tooth cutter, a modified cutter, and a ring-tooth roller. Research was carried out both by classical methods of tillage and with the use of CTT. Soil cultivation was carried out to a depth of 15, 20, and 25 cm at movement speeds of 0.69, 1.0, 1.25, and 1.53 m/s. The physical properties of the soil, runoff, soil loss, moisture storage efficiency and wheat yield were studied. According to the results of the study, the application of CTT increased the rate of infiltration, increased the efficiency of moisture accumulation, reduced runoff and ensured the highest yield of wheat. The best indicators of the studied parameters occurred when the soil was worked to a depth of 20 cm in the range of speeds from 1.0 to 1.25 m/s. However, as the authors note, the research is incomplete, and the results are valid only for the types of soils under study.

In turn, the authors of work [24] recommend using ring-spur rollers for loosening the upper and compacting the seed layers of the soil, breaking up the clods and leveling the plowed field. However, no studies have been conducted on the effectiveness of the process of planting crops and creating a high-quality compacted seed layer on turf-podzolic and forest soils of the Polissya zone. In particular, the influence of the specific load of the mechanized tool on the soil, the number of passes for which the desired soil compaction can be achieved, etc., was not investigated.

Analyzing works [10–25], we can conclude that all research results have narrow limits of their application and are valid only for those types of soils that were studied. The existing type of rollers and the recommended modes of operation do not always correspond to the tasks that are set before them. Therefore, research should be aimed at substantiating the parameters and operating modes of working bodies for rolling under certain conditions and technological tasks.

3. The aim and objectives of the study

The purpose of the research is to improve the quality of the cultivation of the soil environment by determining the rational structural and technological parameters of the rolling working bodies. This will make it possible, depending on the working conditions, to select such a specific load on the ring-toothed roller, which will ensure a rational layer-by-layer density of the soil and a high uniformity of the density of the soil in the processed layer. This allows – to preserve moisture in the soil, increase the yield of agricultural crops, and preserve the fertility of the soil.

To achieve the goal, the following tasks were set:

– to investigate the influence of the type and parameters of rolling working bodies (specific load, multiplicity of passes, operating speed of the unit) on the distribution of layer density of the soil;

– to investigate the influence of the type and parameters of the rolling working bodies (specific load, multiplicity of passes, operating speed of the unit) on the degree of density inhomogeneity in the soil layer.

4. The study materials and methods

The object of our research is the process of layer-by-layer compaction of the soil environment after pre-sowing tillage.

The working hypothesis assumes that the layer-by-layer density of the soil and its homogeneity depend on the specific pressure, the multiplicity of the compacting effect, time and intensity of the effect. The specified parameters, in turn, depend on the speed of rotational and translational movement of the roller (deformer).

The following should be taken as assumptions:

– the rotation of the roller is carried out without slipping;

– the initial layer-by-layer moisture and density of the soil before conducting experimental studies are constant;

– uniformity of movement of the unit is considered at the specified speed;

– the background of the field is uniform, without weeds.

When studying the interaction of rollers with the soil, the following determining factors were chosen:

– x_1 – specific load, P, kg/m;

– x_2 – the number of passes, n, times;

– x_3 – operating speed of the unit, V, km/h.

As a response function, $(Y_1', Y_2', Y_3', Y_4', Y_5', Y_6')$ is chosen – soil density in layers ρ, g/cm^3: 0...5; 5...10; 10...15; 15...20; 20...25; 25...30 cm.

In addition, during the experiment, an array of data was built to assess the heterogeneity of soil density in layers 0...5 and 5...10 cm.

The design of experimental studies was carried out on the basis of the standard B-optimal plan of the second order for three factors [26]. Thus, 15 experiments were performed with a tenfold repetition on six horizons, located with a step of five centimeters. After the soil was rolled along the horizons at the points removed from the track of the agricultural movers (not less than 0.3 m), the density was measured along the track and width of the roller. The number of measurements was 100.

When choosing a field for the experiment, location, topography, and crop rotation were taken into account. After dividing the field into sections, according to the procedure given in [27], soil moisture and density were determined.

To determine the density of the soil by layers and to study its heterogeneity, the RPP-2 radioisotope density meter was used, which allowed determining the density of the soil in its natural state in real time. The principle of operation of the densitometer was based on the weakening of the intensity of a beam of gamma quanta when passing through a layer of matter. The degree of attenuation was proportional to the density of this substance.

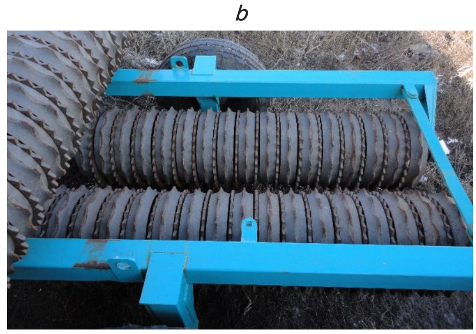
A probe with a source of radioactive radiation was inserted into the soil to the required depth. Having determined the intensity of gamma quanta passing through the studied horizon using the SIP-1 pulse counter, the readings were recorded for the purpose of further calculation and obtaining real values according to tared tables. Data processing and recalculation were carried out by the software of the device. The manufacturer of RPP-2 and SIP-1 devices is Kyiv State Research Plant «Etalon». The devices are manufactured in accordance with DSTU B V.2.1-26:2009 «Soils. Methods of radioisotope measurement of density and humidity».

The studied areas were located 150 m from the edge of the field to exclude the influence of turning lanes. It was necessary to comply with the requirement to avoid hitting the tracks of machine-tractor units. The experimental setup included a trailed roller with loading platforms (according to the experimental plan). The weight of the roller was determined in the «working condition» on the weighing platform.

To load the rollers and vary the «specific load on the soil» parameter, rubber-coated discs of the weightlifting barbell were used (Fig. 1).

a

b



c

Fig. 1. Working bodies for rolling: *a* — smooth water-filled roller; *b* — ring-spur roller; *c* — ring-tooth roller

To study the influence of different types of sealing rollers, a study of ring-tooth, ring-spur, and smooth-water-filling rollers was carried out. The main factors studied in the specified soil and climatic conditions (soil type – sod-podzolic) are listed in Table 1.

Test conditions: soil type – sod-podzolic (pre-treatment – plowing to a depth of 30 cm under steam and pre-sowing soil treatment to a depth of 8...10 cm). Soil moisture and density at the time of the experiments are given in Table 2. It should be noted that the most typical conditions of application of working bodies for rolling were chosen according to soil moisture, taking into account the assumptions made in the work.

Table 1

Factors and their levels of variation in field experiments

Level of variation of factors	Ring-toothed			Ring-spur			Smooth-water-filled		
	x_1 (*P*), kg/m	x_2, times	x_3 (*V*), km/h	x_1 (*P*), kg/m	x_2, times	x_3 (*V*), km/h	x_1 (*P*), kg/m	x_2, times	x_3 (*V*), km/h
Top +1	650	3	9	550	3	9	550	3	9
Main 0	575	2	6	450	2	6	475	2	6
Lower –1	500	1	3	350	1	3	400	1	3
Interval *h*	75	1	3	100	1	3	75	1	3

Table 2

Conditions for conducting experiments to study the influence of rollers on the density of sod-podzolic soil

Horizon, cm	Density, g/cm^3
0–5	0.92±0.02
5–10	1.08±0.02
10–15	1.15±0.03
15–20	1.19±0.02
20–25	1.20±0.04
25–30	1.25±0.03

The results of the study were treated using Microsoft Excel 2016.

5. Results of investigating the influence of the type and parameters of rollers on the distribution of layer-by-layer density and density heterogeneity in the soil layer

5. 1. Results of examining the influence of the type and parameters of the rolling working bodies on the distribution of the layer density of the soil

The results of field studies of working bodies for rolling (Fig. 1) showed that smooth water-filled rollers are not suitable for use on sod-podzolic soils due to the high unevenness of compaction of both the upper and lower layers of the arable horizon. It should be noted that at a speed of 6 km/h, the value of the root mean square deviation of the soil density in a layer of 5...10 cm for a smooth water-filled roller is 5 times higher compared to a ring-toothed roller. Therefore, it is not appropriate to give the results of research on the use of a water-filled roller.

In the study, one of the technological parameters was the number of passes of the roller across the field. However, about 80...90 % of soil compaction occurs as a result of the first pass of the unit. It is economically profitable and ecologically expedient to solve the issue of creating the optimal layer density of the soil in one pass of the unit. As a result of experimental studies, the regression equation of the change in soil density after its cultivation with ring-spur and ring-tooth rollers was built, depending on the specific load (x_1), the number of passes (x_2), and the speed of movement of the unit (x_3). Research was conducted for layers 0...5, 5...10, 10...15, 15...20 cm:

$$Y_i' = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1x_2 + b_5x_1x_3 + b_6x_2x_3 + b_7x_1x_2x_3 + b_8x_1^2 + b_9x_2^2 + b_{10}x_3^2. \quad (1)$$

The coefficients of regression equation (1) in normalized form are given in Tables 3, 4.

Values of the regression coefficients for estimating the change in soil density for rollers in the case of one pass through the field are given in Table 4.

Analysis of the results of experimental studies showed that the ring-spur roller does not compact the layers of 0...5 cm and 5...10 cm (Fig. 2, 3) and over-compacts the layer of 15...20 cm. Without changing the design parameters of the roller, it is impossible due to the variation in the speed of the unit and specific load to obtain optimal compaction of sod-podzolic soil in the seed layer. Over-compaction of the lower soil layers and poor compaction of the upper ones contradicts the agrotechnical requirements for pre-sowing soil treatment. Therefore, in this zone, the ring-spur roller is more suitable for crushing clods and additional loosening of the soil than for compacting the seed layer of the soil.

Table 3

Values of the regression coefficients for estimating the change in soil density

Regression equation coefficient	Ring-toothed				Ring-spur			
	0–5 cm	5–10 cm	10–15 cm	15–20 cm	0–5 cm	5–10 cm	10–15 cm	15–20 cm
b_0	1.236	1.347	1.396	1.410	1.020	1.280	1.330	1.340
b_1	0.096	0.062	0.066	0.071	0.029	0.013	0.025	0.031
b_2	0.078	0.066	0.059	0.047	0.020	0.023	0.027	0.030
b_3	–0.010	–0.015	–0.014	–0.012	–0.011	–	–0.009	–0.008
b_4	0.035	–0.014	–0.002	0.018	–0.021	–	–0.015	–0.017
b_5	0.026	0.011	0.008	–0.020	0.013	0.016	0.012	–
b_6	–0.014	–0.004	0.004	0.027	–	–0.050	–	0.014
b_7	0.018	0.006	–0.002	–0.012	–	–	–0.009	–0.026
b_8	–0.063	–0.018	–	–0.011	0.025	–	–0.020	–0.031
b_9	0.017	0.020	–	0.017	0.038	–0.023	–0.014	–
b_{10}	0.020	0.006	–0.002	–0.031	–0.037	–0.013	–0.009	–

Table 4

Values of the regression coefficients for estimating the change in soil density for rollers in the case of one pass on the field

Regression equation coefficient	Ring-spur				Ring-toothed			
	0–5 cm	5–10 cm	10–15 cm	15–20 cm	0–5 cm	5–10 cm	10–15 cm	15–20 cm
b_0	1.038	1.234	1.289	1.31	1.175	1.301	1.337	1.38
b_1	0.05	0.013	0.04	0.048	0.061	0.076	0.068	0.053
b_2	–	–	–	–	–	–	–	–
b_3	–0.011	0.05	–0.009	–0.022	0.004	–0.011	–0.018	–0.039
b_4	–	–	–	–	–	–	–	–
b_5	0.013	0.016	0.021	0.026	0.008	0.005	0.01	–0.008
b_6	–	–	–	–	–	–	–	–
b_7	–	–	–	–	–	–	–	–
b_8	0.025	0	–0.02	–0.031	–0.06	–0.018	0	–0.011
b_9	–	–	–	–	–	–	–	–
b_{10}	–0.037	–0.013	–0.009	0	0.02	0.006	–0.002	–0.031

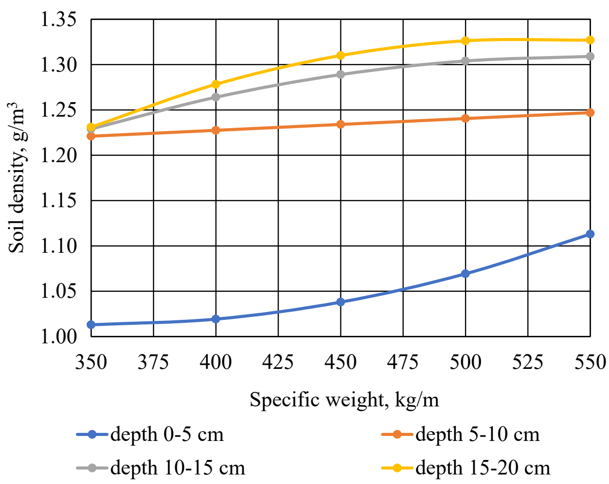


Fig. 2. Influence of the specific load of the ring-spur roller on the distribution of the layer density of the soil for one pass at a speed of 6 km/h

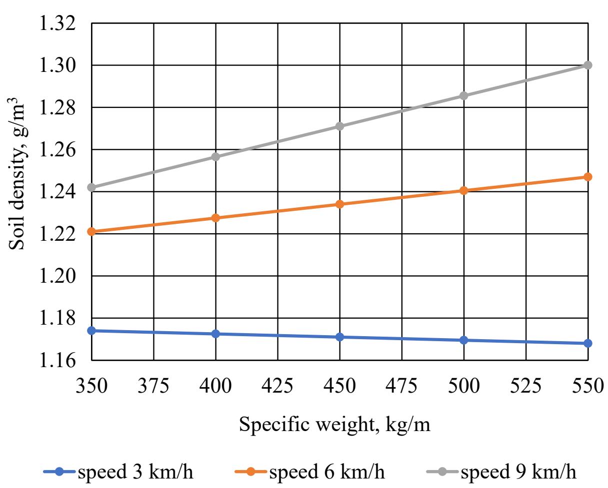


Fig. 3. Comparative analysis of the impact of the specific load of the ring-spur roller on the density of the soil layer 5...10 cm at speeds of 3, 6, and 9 km/h

Analysis of the results of the study of the ring-spur roller shown in Fig. 3, confirms the above conclusion. An increase in the specific load leads to partial over-compaction of the 10...15 and 15...20 cm layers. That is, the ring-spur roller is not suitable for compacting the surface and seed layers. An increase in the specific load on the roller (for example, at a speed of 3 km/h), on the contrary, leads to the immersion of its rings in the soil, which causes more loosening and mixing of the soil of the surface layer (Fig. 3). Increasing the rolling speed and setting the maximum possible specific load can raise the average density of the soil in the 0...5 cm layer to 1.12 g/cm^3 (Fig. 2). At the same time, the root mean square deviation of the density increases several times when the optimal density of the seed layer is not reached (1.2...1.4 g/cm^3). This makes no sense neither from an economic nor from an agro-ecological point of view.

The ring-tooth roller is more suitable for use on sod-podzolic soils (Fig. 4, 5). It uniformly compacts the top and seed layers at a speed of up to 4 km/h. At a rolling speed of about 9 km/h, the indicators of its work approach the technological process of rolling with the formation of the optimal average layer-by-layer density of the soil, and at the initial indicators of specific weight (Fig. 4).

However, with the roller operating modes, which provide optimal density in the 0...5 and 5...10 cm layer, the lower soil layers are over-compacted (Fig. 4).

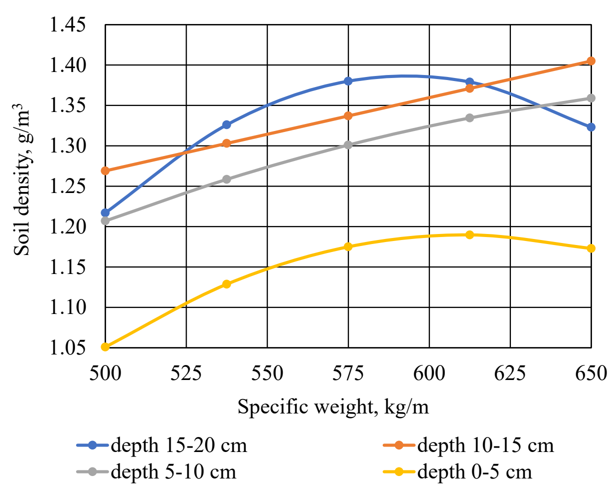


Fig. 4. Effect of the specific load of the ring-tooth roller on the distribution of the layer density of the soil for one pass at a speed of 6 km/h

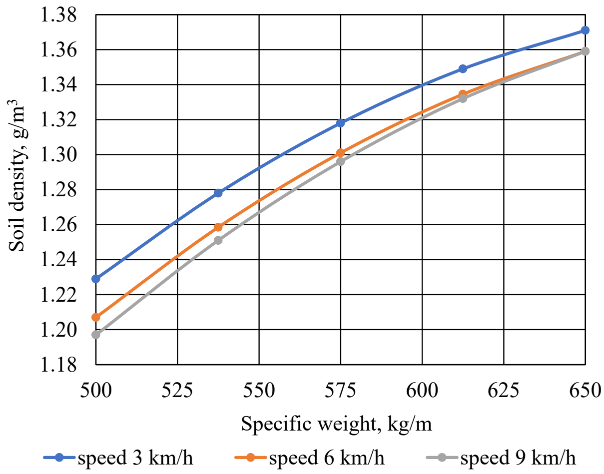


Fig. 5. Comparative analysis of the impact of the specific load of the ring-tooth roller on the density of the soil layer of 5...10 cm at speeds of 3, 6, and 9 km/h

5. 2. Results of investigating the influence of the type and parameters of the rolling working bodies on the degree of density inhomogeneity in the soil layer

According to our research results (at least 100 layer-by-layer measurements were carried out during the research, this allows determining the average value and root mean square deviation of the layer-by-layer density of the soil), at low rolling speeds – from 3 to 6 km/h – the mean square deviation of the density values in each layer is at the same level. With an increase in speed up to 9 km/h, the value of increases by 50 % (Fig. 6).

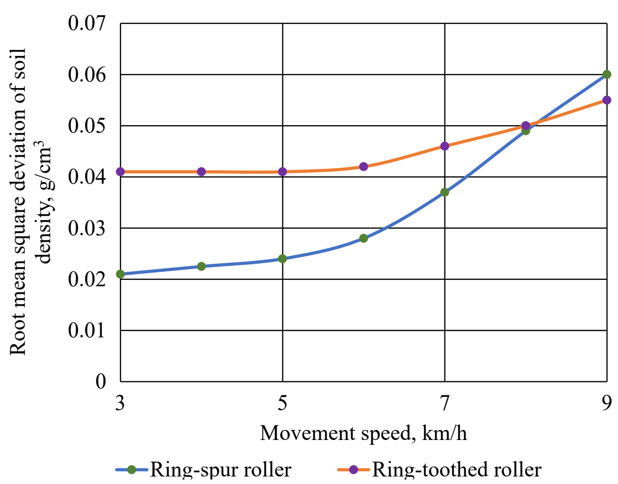


Fig. 6. Influence of the speed of the roller on the root mean square deviation of the soil density in a layer of 5...10 cm with one pass of the roller and a specific weight of the roller of 550 kg/m

According to [17, 21], an increase in the variance of density values leads to a loss of productivity. Since at low speeds it is impossible to achieve a given uniform density of the soil, the standard ring-toothed roller (of a given weight and diameter) does not sufficiently meet the requirements for the formation of optimal soil density.

It is necessary to note the peculiarity of the management of structureless soils of this region. Under the condition of their deformation, the density of the soil increases with increasing depth. This significantly complicates the solution of the problem, and, unfortunately, it cannot be done without additional research (in which the optimization parameter is «agricultural crop yield»).

One of the criteria for evaluating the work of rolling working bodies can be an increase in the layer-by-layer density of the soil relative to the initial one (Table 2).

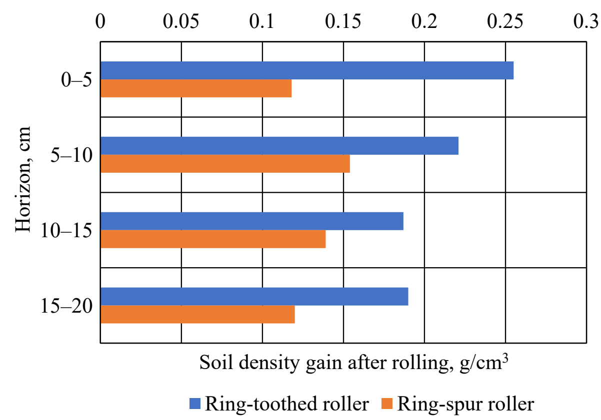


Fig. 7. The nature of distribution of the increase in the layer density of soil during rolling at a speed of 6 km/h with a specific load on the soil of 575 kg/m for a ring-tooth roller and 450 kg/m for a ring-spur roller

Fig. 7 shows that the maximum increase in density occurs in a layer of 5...10 cm for the ring-spur roller. At the same time, the intensity of soil density growth in the lower layers increases significantly and becomes 42 % higher after the applied load. Thus, the weight of the set-in-motion upper layers affects the density increase in the 15...20 cm layer.

For the ring-tooth roller, the pattern is different: the ring-tooth roller in the contact zone has an almost continuous surface (the rings are closed) with evenly distributed pressure. As the surface of the roller under a significant load sinks into the soil, the compaction of the surface layer increases and, at the same time, the contact area increases (the arc of the circle increases) and, as a result, the specific pressure on the subsequent layers of the soil decreases.

6. Discussion of results of investigating the influence of the type and parameters of rollers on the physical and mechanical properties of soil

In world practice, such concepts as «differentiated construction of the arable horizon» and «optimization of the physical and mechanical properties of the arable horizon» are considered universally recognized [22]. The arable horizon as a result of mechanical processing should have a differentiated structure and be divided into three layers: above-sown, sown, and under-sown with a certain (optimal) density of the sown layer [22]. The task of the over-sowing layer is to preserve moisture in the seed and under-sowing layers, smooth out adverse weather phenomena, and protect the soil from erosion processes. The task of the seed layer is to create favorable conditions for the initial stage of plant development from seeds. The task of the seed layer is to create favorable conditions for the development of the root system of plants, the accumulation and preservation of moisture in the arable and root-rich horizons.

Many years of research [1–25, 28] have proven that different models of the optimal structure of the arable horizon correspond to different soil and climatic conditions. Based on our own experience [21, 22] and the research of foreign colleagues [11–13, 25], special attention should be paid to the quality of the preparation of the topsoil and seed layers. It is the quality of the preparation of these layers that ensures friendly seedlings and the development of plants at an early stage, and also significantly affects the formation of the future harvest.

The results of the study of the distribution of the layer density of the soil depending on the type and parameters of the rolling working bodies showed that the specific load of the ring-spur roller increases the layer density of the soil (Fig. 2). At the same time, the greatest increase in compaction is characteristic of a soil layer of 15...20 cm because after pre-sowing cultivation, the soil is loose and the roller rings «sink» below the seed layer, compacting this layer. At the same time, the specific load applied to the ring-tooth roller (Fig. 4) increases the layer-by-layer density of the soil only in a layer of 15...20 cm. For a soil layer of 0...5 cm, the maximum increase in soil density is achieved only with a specific load of 575 up to 625 kg/m. In the specified range of loads for a layer of 15...20 cm, the increase in soil density begins to decrease, that is, the surface and seed layers of the soil perceive most of the load. This is explained by the geometry of the ring-tooth roller since this type of roller has an almost continuous surface in the contact zone (the rings are closed), which ensures an even distribution of pressure on the surface. As the roller «dips» into the soil under the influence of the load, the degree of compaction of the surface layer increases, therefore, the contact area of the surface of the roller with the soil increases (circular arc). This reduces the amount of specific pressure on the lower layers of the soil. This type of roller is known as «Cambridge» and is widely distributed in the world.

A specific load of 450 kg/m, applied to a ring-spur roller at a speed of 3 km/h, almost does not change the value of the density of the soil in a layer of 5...10 cm. However, at a speed of the roller of 6 and 9 km/h, an increase in density is observed soil in a layer of 5...10 cm under the action of the specific load (Fig. 3). This phenomenon is explained by the fact that an increase in the speed of movement of the roller causes an increase in the energy of the rotational movement of the rings of the roller, which, in turn, is directed to the compaction of the soil.

When using a ring-tooth roller (Fig. 5), the application of specific load increases the layer-by-layer density of the soil in a layer of 5...10 cm at all values of the speed of the roller. However, with an increase in the speed of the roller, its compacting effect on the soil decreases only slightly. This is due to the fact that for rollers with a continuous surface (ring-toothed) there is a range of speeds and specific loads at which the roller seems to «float», which reduces the intensity of soil compaction. Given the defined characteristics of the soil layer, there is a «counteraction» of this layer to the compacting effect of the roller, which is explained by the viscosity of the soil. At the same time, the viscosity of the soil is functionally related to such parameters as its mechanical composition, humidity, and rate of deformation. Therefore, in a certain range of movement speeds, under the influence of inertial forces, the roller «floats», and the energy of its rotational movement is directed, to a greater extent, to the crushing of lumps than to compaction.

The dependence of the degree of heterogeneity of the density in the soil layer on the parameters of the rollers indicates that the speed of movement of the rollers up to 6 km/h does not affect the root mean square deviation of the density of the soil in a layer of 5...10 cm (Fig. 4). This is valid for one pass of the roller with a specific load of 550 kg/m on the ring-toothed roller and 450 kg/m on the ring-spur roller. With a further increase in the speed of movement, the root mean square deviation of the soil density under similar conditions begins to increase in proportion to the increase in speed (Fig. 6). As mentioned, with an increase in the speed of the rollers, it seems to «float», the intensity of rotation of the discs and rings increases, balancing, even static, rings and discs are absent, unbalanced masses cause dynamic unbalanced movement of the rollers. This leads to an uneven effect of the surface of the rollers on the soil environment.

During rolling with a ring-spur roller with a specific load on the soil of 450 kg/m and a movement speed of 6 km/h, the greatest heterogeneity of soil density occurs in the 5...10 cm layer. Smaller heterogeneity is observed in the 0...5 cm and 10...20 cm layers (Fig. 7). This is due, first of all, to the «sinking» of the rings into the soil to this depth under the influence of a significant load. Under similar conditions of using a ring-tooth roller with a specific load on the soil of 550 kg/m, the layer-by-layer density of the soil changes mostly in the 0...5 cm layer. In the 10...15 cm and 15...20 cm layers, the change in soil density is practically the same unchanged. Due to the continuous surface of the ring-spur roller, the main load applied to the surface of the roller is distributed in the surface layer of the soil, and the lower layers, in turn, are compacted to a lesser extent. It can be predicted that the subsoil horizon will also not undergo significant overcompaction since the specific load will be distributed mainly in the arable horizon. This is very important for the further formation of the water balance of arable and subsoil horizons. The results are partially confirmed by the findings reported in [1]. However, the authors of the work investigated the change in the volume density of the soil (in particular, such phenomena as subsidence and shrinkage of the soil) under the influence of various methods of its cultivation. A mathematical model is also presented for predicting the change in bulk density of the soil under various conditions.

The uniqueness of our studies of the rolling process using ring-spur and ring-tooth rollers is that the layer-by-layer distribution of density and the heterogeneity of soil density were investigated in a wide range of specific loads and movement speeds. Also unique is the method that involves the use of non-destructive control of soil density in layers. This allows us to ensure the superiority of the current research compared to the similar one [8], where soil sampling methods were used. And also compared to [7], in which more limited ranges of changes in specific loads and movement speeds are used.

Our results ensure the improvement of the quality of the cultivation of the soil environment by determining the rational structural and technological parameters of ring-spur and ring-tooth rollers. This is enabled by selecting the specific loads and speeds of the rollers in such a way as to ensure a layer-by-layer distribution of soil density and its heterogeneity, which to the greatest extent meets the requirements of the corresponding field crops.

However, present research has application limits: the type of soils on which this research was conducted; soil moisture range. The sod-podzolic soil had a determined moisture content from 26.3 to 28.2 % and was previously plowed to a depth of 30 cm under steam and required pre-sowing soil treatment.

The shortcomings of the research include specific soil and climatic conditions; they are zonal in nature, and the results are limited to the conditions of conducting the experiment in terms of humidity and initial layer-by-layer density of the soil.

However, the methodological foundations and research results can be the basis for conducting comparative studies under other soil and climatic conditions when applying other techniques of soil cultivation.

Expanding research for the main types of soils and methods of their cultivation will provide an opportunity to select specific loads and roller speeds in such a way as to ensure layer-by-layer distribution of soil density and its heterogeneity. This meets the requirements of the main field crops to the greatest extent.

In order to generalize and systematize zonal practical results (regression equations) in this direction, further experimental studies should be conducted according to the following scheme:

1) «Condition of the soil environment $\leftrightarrow$ moisture and density of the soil» $\rightarrow$ systematization of soils, determination of the working conditions of soil processing working bodies;

2) «Working bodies $\leftrightarrow$ technological task» $\rightarrow$ technological and energy indicators of work;

3) «Working bodies $\leftrightarrow$ soil environment» $\rightarrow$ quality indicators of work;

4) «Soil environment $\leftrightarrow$ yield of agricultural crops» $\rightarrow$ efficiency of soil cultivation;

5) Construction of information databases for further use of experimental research results. Evaluation of the operation of tillage machines based on the results obtained without additional field tests.

7. Conclusions

1. As a result of investigating the influence of the type and parameters of the rolling working bodies on the distribution of the layer density of the soil, one should note the following:

– it is economically and ecologically more expedient to solve the issue of creating the optimal layer-by-layer density of the soil in one pass of the unit;

– smooth water-filled rollers are not suitable for use on sod-podzolic and forest soils due to the high unevenness of compaction of both the upper and lower layers of the arable horizon;

– the ring-spur roller is more suitable for crushing clods, additional loosening of the soil, because under certain operating conditions it over-compacts the lower and poorly compacts the upper layers of the soil, contrary to agrotechnical requirements for pre-sowing soil treatment.

– the ring-toothed roller is the best among the studied types of rollers in terms of the main performance indicators, which meets the requirements for the pre-sowing treatment of sod-podzolic and forest soils. Its use makes it possible to achieve the specified density of the soil in the sowing layer without significant over-compaction of the subsoil (one pass, specific load on the soil 350 kg/m, unit speed up to 6 km/h);

2. As a result of examining the influence of the type and parameters of the rolling working bodies on the degree of density inhomogeneity in the soil layer, one should note the following:

– limitation on the speed of movement of the unit (no more than 6 km/h for sod-podzolic soil) is caused by a sharp increase in the mean square deviation of the soil density in a layer of 5...10 cm at $V>6$ km/h;

– for rollers with a continuous surface, there is a range of speed and specific load in which the roller seems to «float» and reduces the intensity of soil compaction. At certain viscosity indicators of the soil, it counteracts the effect of the compacting roller. At the same time, the viscosity parameter, in turn, is functionally related to the mechanical composition, humidity, and rate of soil deformation;

– the derived regression equation makes it possible, depending on the working conditions, to select the specific load on the ring-toothed roller to ensure a rational layer-by-layer density of the soil and high homogeneity of the density of the soil in the processed layer.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

The data will be provided upon reasonable request.

References

1. Wang, Y., Zhang, Z., Guo, Z., Chen, Y., Yang, J., Peng, X. (2023). In-situ measuring and predicting dynamics of soil bulk density in a non-rigid soil as affected by tillage practices: Effects of soil subsidence and shrinkage. Soil and Tillage Research, 234, 105818. doi: https://doi.org/10.1016/j.still.2023.105818
2. Alletto, L., Pot, V., Giuliano, S., Costes, M., Perdrieux, F., Justes, E. (2015). Temporal variation in soil physical properties improves the water dynamics modeling in a conventionally-tilled soil. Geoderma, 243-244, 18–28. doi: https://doi.org/10.1016/j.geoderma.2014.12.006
3. Canali, S., Campanelli, G., Ciaccia, C., Leteo, F., Testani, E., Montemurro, F. (2013). Conservation tillage strategy based on the roller crimper technology for weed control in Mediterranean vegetable organic cropping systems. European Journal of Agronomy, 50, 11–18. doi: https://doi.org/10.1016/j.eja.2013.05.001
4. Wen, L., Peng, Y., Zhou, Y., Cai, G., Lin, Y., Li, B. (2023). Effects of conservation tillage on soil enzyme activities of global cultivated land: A meta-analysis. Journal of Environmental Management, 345, 118904. doi: https://doi.org/10.1016/j.jenvman.2023.118904
5. Sharma, S., Singh, P. (2023). Tillage intensity and straw retention impacts on soil organic carbon, phosphorus and biological pools in soil aggregates under rice-wheat cropping system in Punjab, north-western India. European Journal of Agronomy, 149, 126913. doi: https://doi.org/10.1016/j.eja.2023.126913

6. Douglas, J. T., Koppi, A. J. (1997). Soil structural quality: a case study of soil macropore attributes after seedbed preparation with different wheel traffic systems. Soil and Tillage Research, 41 (3-4), 249–259. doi: https://doi.org/10.1016/s0167-1987(96)01096-3
7. James, I. T., Shipton, P. M. R. (2012). Quantifying compaction under rollers using marker tracing image analysis. Soil and Tillage Research, 120, 40–49. doi: https://doi.org/10.1016/j.still.2012.01.006
8. Tong, J., Zhang, Q., Guo, L., Chang, Y., Guo, Y., Zhu, F. et al. (2015). Compaction Performance of Biomimetic Press Roller to Soil. Journal of Bionic Engineering, 12 (1), 152–159. doi: https://doi.org/10.1016/s1672-6529(14)60109-8
9. Tong, J., Zhang, Q., Chang, Y., Chen, D., Dong, W., Zhang, L. (2014). Reduction of soil adhesion and traction resistance of ridged bionic press roller. Transactions of the Chinese Society for Agriculture Machinery, 45, 135–140.
10. Rücknagel, J., Rücknagel, S., Christen, O. (2012). Impact on soil compaction of driving agricultural machinery over ground frozen near the surface. Cold Regions Science and Technology, 70, 113–116. doi: https://doi.org/10.1016/j.coldregions.2011.09.004
11. Colombi, T., Torres, L. C., Walter, A., Keller, T. (2018). Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth – A vicious circle. Science of The Total Environment, 626, 1026–1035. doi: https://doi.org/10.1016/j.scitotenv.2018.01.129
12. Premrov, A., Cummins, T., Byrne, K. A. (2018). Bulk-density modelling using optimal power-transformation of measured physical and chemical soil parameters. Geoderma, 314, 205–220. doi: https://doi.org/10.1016/j.geoderma.2017.10.060
13. Altikat, S., Celik, A. (2011). The effects of tillage and intra-row compaction on seedbed properties and red lentil emergence under dry land conditions. Soil and Tillage Research, 114 (1), 1–8. doi: https://doi.org/10.1016/j.still.2011.03.003
14. Mileusnić, Z. I., Saljnikov, E., Radojević, R. L., Petrović, D. V. (2022). Soil compaction due to agricultural machinery impact. Journal of Terramechanics, 100, 51–60. doi: https://doi.org/10.1016/j.jterra.2021.12.002
15. Moinfar, A., Shahgholi, G., Gilandeh, Y. A., Kaveh, M., Szymanek, M. (2022). Investigating the effect of the tractor driving system type on soil compaction using different methods of ANN, ANFIS and step wise regression. Soil and Tillage Research, 222, 105444. doi: https://doi.org/10.1016/j.still.2022.105444
16. Golub, G., Chuba, V., Achkevych, V., Krushelnytskyi, V., Tsyvenkova, N. (2023). Modeling of the running system pressure on the soil depending on the structural parameters of the tractors. INMATEH Agricultural Engineering, 69 (1), 369–378. doi: https://doi.org/10.35633/inmateh-69-34
17. Kushnarev, A. S., Kochev, V. I. (1989). Mekhaniko-tekhnologicheskie osnovy obrabotki pochvy. Kyiv: Urozhay, 144.
18. Kachinskiy, N. A. (1958). Otsenka osnovnykh fizicheskikh svoystv pochv v agronomicheskikh tselyakh i prirodnogo plodorodiya po ikh mekhanicheskomu sostavu. Pochvovedenie, 5, 10–13.
19. Bulyhin, S. Yu., Vitvitskyi, S. V. (2021). Ahrofizyka gruntu. Kyiv: Vydavnytstvo, 315.
20. Hutsol, O. P., Kovbasa, V. P. (2016). Obgruntuvannia parametriv i rezhymiv rukhu gruntoobrobnykh mashyn z dyskovymy robochymy orhanamy. Kyiv, 145.
21. Shevchenko, I. A., Alba, V. D. (1994). Vliyanie pokazateley raboty kol'chato-zubovogo katka na izmenenie plotnosti pochvy i urozhay sel'skokhozyaystvennykh kul'tur. Trudy mezhdunarodnoy konf. «Modelirovanie protsessov i tekhnologicheskogo oborudovaniya v s.kh.». Melitopol': TGATA, 34–39.
22. Shevchenko, I. A. (2002). Obgruntuvannia tekhnolohiy ta tekhnichnykh zasobiv dlia obrobitku gruntiv na bazi yikh ahrofizychnykh pokaznykiv. Kyiv, 382.
23. Shustik, L., Pogoriliy, V., Nilova, N., Gaiday, T., Stepchenko, S., Sidorenko, S. (2020). Rollers of different constructions. Engineering analysis. Technical and Technological Aspects of Development and Testing of New Machinery and Technologies for Agriculture of Ukraine, 27 (41). doi: https://doi.org/10.31473/2305-5987-2020-2-27(41)-9
24. Shustik, L., Pogoriliy, V., Nilova, N., Gaidai, T., Stepchenko, S., Sidorenko, S. (2021). Crosskill and star-wheeled rollers. Functional and dynamic tests. Technical and Technological Aspects of Development and Testing of New Machinery and Technologies for Agriculture of Ukraine, 28 (42). doi: https://doi.org/10.31473/2305-5987-2021-1-28(42)-7
25. Salem, H. M., Valero, C., Muñoz, M. Á., Gil-Rodríguez, M. (2015). Effect of integrated reservoir tillage for in-situ rainwater harvesting and other tillage practices on soil physical properties. Soil and Tillage Research, 151, 50–60. doi: https://doi.org/10.1016/j.still.2015.02.009
26. Vazhynskyi, S. E., Shcherbak, T. I. (2016). Metodyka ta orhanizatsiya naukovykh doslidzhen. Sumy: SumDPU imeni A. S. Makarenka, 260.
27. Bobyliev, V. P., Ivanov, I. I., Proidak, Yu. S. (2014). Metodolohiya ta orhanizatsiia naukovykh doslidzhen. Dnipropetrovsk: IMA-press, 643.
28. Asoodar, M., Mohajer, F. (2009). Effects of different tillage and press wheel weight on dryland wheat grain production. Technology and Management to Increase the Efficiency in Sustainable Agricultural Systems. Rosario. Available at: https://journals.sfu.ca/cigrp/index.php/Proc/article/view/103