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SUBSTANTIATING THE STRUCTURAL AND TECHNOLOGICAL PARAMETERS OF TILLAGE ROTARY X-LIKE WORKING BODIES

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The object of this study is the process of grinding and crumbling the surface layer of the soil with turf of winter crops by X-shaped working bodies. It has been established that the use of a grinding group based on X-shaped rotary working bodies as part of combined tillage tools makes it possible to preliminary loosen the surface layer of heavy soils (over-dried or overmoistened). It was established that the optimal values of the parameters of the section of the X-shaped rotary working bodies for the quality of loosening the soil in a layer of 0–10 cm at a depth of cultivation of 14±2 cm depend on the speed of the unit. Thus, at a speed of movement of the unit of 2 m/s, the optimal value of the diameter of the rotor blade is 335.9 mm, the distance between the axes of the rotor batteries is 316.4 mm, and the distance between the rotor blades in the battery is 195.6 mm. At a unit movement speed of 2.5 m/s, the optimal values of these parameters are 331.2, 325.7, and 211.3 mm, respectively, and at a unit movement speed of 3 m/s – 330.1, 346.8, and 106.1 mm. It was also established that the stability of the movement of the X-shaped working bodies according to the root mean square deviation of the working depth increases with the increase in the speed of the unit. Thus, at a unit movement speed of 2.5 m/s, the root mean square deviation of the soil tillage depth is 1.21 cm, at a unit movement speed of 3 m/s – 1.07 cm, and at a unit movement speed of 3.5 m/s – 0.63 cm. It was also established that the stability of the movement of the working bodies according to the depth of cultivation decreases with an increase in the speed of movement of the unit. Thus, at a movement speed of the unit of 2.5 m/s, the average soil tillage depth is set at the level of 13.1 cm, at a movement speed of the unit of 3 m/s – 12.6 cm, and at a movement speed of the unit of 3.5 m/s – at the level of 11.9 cm

Keywords: surface tillage, X-shaped rotary working bodies, soil loosening quality

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1. Introduction

Tillage is one of the most energy-intensive and labor-intensive processes in the system of agrotechnical measures aimed at improving the agrophysical properties of the arable layer and increasing the productivity of field crops. It is one of the effective agrotechnical methods aimed at destroying weeds, combating diseases of agricultural plants and pests [1].

The choice of a set of tillage tools contributes to high-quality tillage of the soil and significantly increases the economic efficiency of crop production. At the current stage of development of the agricultural sector, about 28 % of energy and 26 % of labor costs, calculated on the total costs of growing and harvesting agricultural plants, are the costs of tillage, about half of which is plowing [2].

In order to reduce these costs, a set of plowing machines should be carefully selected. As a rule, this choice significantly depends on the physical and mechanical properties of the soil of a certain soil-climatic zone and the requirements for the quality of loosening the soil and the degree of cultivation of plant residues. Therefore, when choosing a tillage unit, the specified factors should be taken into account in order to create favorable conditions for the course of biological, chemical, physical-chemical, and physical processes in the soil [3].

One of the innovative solutions in the field of soil cultivation is the use of X-shaped rotary working bodies [4]. Tools equipped with X-shaped working bodies are not typical and widespread. The expediency of their use as a part of combined tillage units is due to simplicity of construction, lower energy consumption compared to disc working bodies, lower specific weight. Also, X-shaped working bodies, which are produced by the German company Hankmo, are characterized by better performance indicators regarding the quality of loosening the soil and the degree of cultivation of plant residues [5].

Despite its advantages, in modern tillage technology, this type of working bodies has not yet become popular as a constituent element of tillage tools for surface tillage and has not been studied in detail. Scientific works consider the feasibility and effectiveness of using X-shaped working bodies as part of combined tillage units for processing light soils [6]. At the same time, studies on the practical feasibility of using such assembly units under conditions of heavy (overmoistened or overdried) soils were not conducted.

Therefore, research should be aimed at substantiating the parameters and modes for operating X-shaped rotary working bodies as part of combined tillage units in order to increase their efficiency when working under different field conditions.

2. Literature review and problem statement

Study [7] established that according to the technical and technological characteristics, X-shaped rotary working bodies are able to solve basic tasks of soil cultivation in the surface layer with the cultivation of plant residues. Also, as an alternative to other working bodies, they can be used for the purpose of crushing plant residues with their partial closure in the soil. The main carrier of these working bodies is defined as a combined harrow as an autonomous tool. The study of two modes of harrow speed determined the qualitative (loosening and harvesting plant residues) and operational indicators of its work. The study is incomplete, as it was conducted using a mass-produced tool design. Therefore, the structural and technological parameters of the working bodies were not studied. Also, the work contains contradictions since combined soil crushing with simultaneous application of complex fertilizers is proposed, although only a single-operation tool is considered in the work.

Paper [4] reports the results of a three-year study of the dependence of corn yield on grain and the quality of loosening of the upper soil layer after tillage with and without winter wheat stubble cultivation. Mining was carried out at a depth below the level of the arable layer (25–34 cm). X-shaped rotary working bodies were used for soil cultivation. According to the results of the study, the ability of the X-shaped working bodies in the harrow was noted against the specified background to perform a technological process with the incorporation of up to 40 % of crushed plant residues into the surface layer of the soil. However, as for backgrounds after harvesting corn, the authors note that X-shaped rotary working bodies are able to work on such backgrounds with some limitations [3]. The results of the study have high practical value, but the limitation of application is that they were conducted only for two types of crushed plant residues. Also, in addition to confirming the performance of the X-shaped working bodies in the harrow under the given conditions, no studies were conducted on the influence of the structural and technological parameters of the unit on the quality of loosening the soil.

Work [8] describes an analytical approach to the study of the impact of the construction and technological parameters of tillage tools on the quality of processing the surface layer of the soil and the effectiveness of the combined aggregate under certain soil and climatic conditions. The system analysis and comprehensive assessment of the productivity of the tillage unit involves the compliance of design parameters and combinations of working bodies with specific soil and climatic conditions. At the same time, agrophysical and rheological characteristics of the soil should be taken into account during its cultivation. The approach involves the purposeful choice or «selection» of theoretically justified parameters of working bodies that ensure the necessary quality of the arable horizon in a specific soil-climatic zone (subzone) with minimal energy consumption. This makes it possible to design modern tillage units using zonal information and analytical databases based on systematized soil characteristics. The above creates prerequisites for determining the economic efficiency of tillage bodies at the design stage. The results of the study are undoubtedly useful for the theoretical justification of the design parameters of any tillage unit, including the X-shaped working bodies in the harrow. However, a drawback of the work is the lack of experimental confirmation of the effectiveness of the reported approach.

In the product catalogs by manufacturing companies [9–12], it is noted that, depending on the technological tasks, the soil tillage combined unit should perform surface soil tillage to a depth of 16 cm, and if necessary, provide pre-sowing tillage to a depth of 6–8 cm. This is quite possible to implement after its reconfiguration. At the same time, the ability to perform high-quality mulching of the soil with plant residues with the tool in one pass makes it possible to prevent erosion processes and preserve soil fertility. As noted in [10], it is advisable to use X-shaped working bodies instead of spherical disks as the first group of working bodies for the processing of sodden, superficially compacted soils. This is the so-called crushing group based on rotary working bodies. The nature of the interaction of the X-shaped working bodies with the soil is similar to a cut-out disk with a diameter of 375...400 mm for four cuts.

The length of the combined unit should be set depending on the type of soil. To reduce the length of the combined unit, it is recommended to set the angle of attack of the battery no more than 15° [11]. At the same time, batteries of X-shaped working bodies should be placed in two rows with partial overlap. This placement of the batteries makes it possible to obtain, after their passage, a high quality of soil crushing, an even profile of the bottom of the furrow, and to solve the issue of self-cleaning of the rotary working bodies.

According to study [12], X-shaped rotary working bodies do not belong to the class of traditional ones. Their task is to reduce the load on the S-shaped elastic working bodies together with grinding the surface layer of the soil. As well as carry out preliminary processing of heavy (overdried or overmoistened soils), grind plant residues on heavily littered backgrounds and backgrounds after corn and sunflower and in gardens. However, research into this area is just beginning.

When studying the impact of structural and technological parameters of a tillage unit with X-shaped working bodies on the quality of tillage, the data provided by the manufacturing companies [9–12] should be used only for comparison. Field studies of the working bodies of harrows with X-shaped working bodies were conducted, practically, for advertising purposes. Research by each firm was conducted on different types of soil (depending on the needs of the customer), the parameters of the working bodies were set to the specified type of soil and did not change until the end of the study. At the same time, the behavior of the tillage unit on the given type of soil and the quality of its tillage were studied. The values of structural and technological parameters of working bodies obtained as a result of research differ in the same range of work modes and on the same types of soils. Therefore, it is advisable to continue conducting field work in order to obtain more data on the dependence of the quality of surface tillage on the design parameters of X-shaped rotary working bodies and to eliminate the existing discrepancy in the already reported results.

A partial solution to this problem is given in [13]. The purpose of the paper was to study the influence of different methods of tillage on the formation of soil crust and to evaluate the effectiveness of soil looseners for improving the germination of cotton seedlings. Experiments were conducted on loamy soil using 4 tillage methods: method *A* (traditional, with plow, disc harrow and roller), method *B* (conservation, with chisel plow, disc harrow and roller), method *C* (traditional, with chisel plow, rotary cultivator, and roller), and method *D* (conservative, with disc harrow and roller). Two types of crust destroyers were studied: roller and blade. Methods *B* and *D* were the most effective in reducing the crust hardness, reducing the penetration resistance to 60–93 kPa compared to 305–408 kPa. The percentage of emergence of seedlings was the highest when using conservation methods *B* (77.8 %) and *D* (78.2 %). In the control plots, the percentage of emergence varied from 51.1 % to 86.2 %, with the sequence of methods: $C<A<B<D$. The application of crust breaking operations increased the percentage of emergence for all methods, with the use of a roller breaker increasing emergence by 27.1 % for method *A* and 34 % for method *C*. Research should be continued for method *D* using a harrow equipped with X-shaped working bodies Probably, the results will be better in terms of the degree of destruction of the crust and the appearance of sprouts, compared to those given in [13], but this requires additional research.

Tillage operations using rotary implements are generally very energy-intensive due to the traction and power of PTO shaft required to prepare the seed bed [14]. In modern science, there is a large enough body of research on modeling PTO-driven implements, in particular rotary tillage machines, to predict traction force, PTO power consumption, and fuel consumption [15, 16]. But these models need experimental verification since the interaction of tillage tools with the soil is a rather complex process due to the heterogeneity of the soil and the ability of the soil to fragment.

As for rotary tillage tools, a significant number of field tests under various soil and climatic conditions have been conducted over the last decade. As a result of the research, the main operating parameters of the tools were obtained, such as traction, tractor speed, torque on the power take-off shaft and rotation frequency [17]. At the same time time, only a few in-depth experimental tests were conducted for plows [18].

In work [18], a combined tillage tool was studied, which consisted of a single deep loosener and a single rotary harrow (equipped with four different types of attachment. The working parameters were as follows: speed of movement (1.79, 2.67, and 3.33 km/h); rotor speed (299 and 526 rpm). Soil type – loam with a bulk density of 1.5–1.7 g/cm^3 with an average moisture content of 16.6 % (per dry weight), able to reduce traction on soil cutting operations by 4.4–11.3 %, depending on attachment type, compared to a single cultivator without attachment. Rotary harrow rotation frequency and travel speed had a significant effect on traction force, PTO power, and total power. The combined tillage implement with attachment IV consumed the least total power. The combined tillage implement with attachments I–IV consumed 13.7, 12.2, 10.5, and 15.3 % less total power, respectively, compared to the total power required for the cultivator and rotary harrow operating separately.

In study [19], the operation of a combined tillage tool consisting of a deep loosener and a rotary harrow was studied. It was planned to reduce costs by reducing the stages of soil treatment. Three tillage operations, two tool movement speeds, and two rotor rotation frequencies were selected as input factors. The size of the soil clods, operating parameters and specific energy consumption of the combined tillage tool were investigated. Increasing the rotor speed from 299 to 526 rpm reduced the average diameter of the soil clod at a depth of 0–200 mm from 22.98 to 19.83 mm and from 31.77 to 26.57 mm for Field 1 and 2, respectively. Specific energy consumption significantly depended on the frequency of rotation of the rotor and the mode of soil cultivation. Specific energy consumption for the combination tillage implement with frame hinge and swivel shank hinge was 10.4 and 21.1 % lower and 18.4 and 24.7 % lower for field sections 1 and 2, respectively, compared to the total energy consumption for the separate use of a deep loosener and a rotary harrow.

The results reported in [18, 19], although they were not directly predicted by the studies of the progenitors and modes of operation of the X-shaped working bodies of the harrow, are nevertheless valuable practical material. Also, the method of conducting research given in [18, 19] can be adapted to studies of the modes of operation of X-shaped working bodies of harrows. Based on the results reported in [18, 19], it follows that the use of a significant number of autonomous soil cultivation operations is not advisable. This leads to significant costs. In addition, time is lost that is critical for surface and pre-sowing tillage. The arable horizon is over-compacted and dried out by additional passes of machine-tractor units and constant movement of the soil environment.

Our review of the above literature reveals that the complex influence of the parameters of the X-shaped rotary working bodies in combination with the speed of movement and the depth of cultivation on the quality of soil cultivation has not been studied. Thus, further research should be aimed at justifying the parameters and modes for operating X-shaped rotary working bodies for work as part of combined tillage units for high-quality processing of heavy soils.

3. The aim and objectives of the study

The purpose of our study is to substantiate the structural and technological parameters of soil-cultivating rotary X-shaped working bodies. This will make it possible to improve the quality of surface tillage by determining rational design parameters for X-shaped rotary working bodies.

To achieve the goal, the following tasks were set:

– to determine the influence of the speed of movement of the unit and the parameters of the X-shaped rotary working bodies on the quality of loosening the soil;

– to determine the influence of the speed of movement of the unit on the stability of the movement of X-shaped rotary working bodies according to the depth of cultivation.

4. The study materials and methods

The object of our study is the process of loosening the soil with the grinding of plant residues by X-shaped rotary working bodies as part of a combined tillage tool.

Given the significantly different working conditions, the scheme of the technological process of the combined unit can be general (Fig. 1) while the working bodies implementing it can be structurally and technologically adapted to specific technological tasks.

The working hypothesis assumes that the quality of loosening the soil, the level of crushing of plant residues, and stability of the movement of working bodies in terms of the depth of cultivation depend on the diameter of the rotor, the distance between the axes of rotation of the rotors, and the distance between the rotors in the section, as well as the speed of translational movement of the sections of the X-shaped working bodies.

The following assumptions were accepted in the study:

– the width (55 mm) and thickness of the knife plate (10 mm) were adopted based on the reliability of the design and analysis of other solutions [12], the cutting angle of the plate in the rotors is 21° [10–12], the radius of curvature of the plate was taken to be 610 mm [20];

– rotation of knife rotors 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 homogeneous with 70 % stubble cover and weediness at the level of 30 %;

– the angle of attack of the battery of knife sections is taken at the level of 14–15° based on the analysis of similar structures [5, 10, 11].

According to the results of experimental studies by manufacturing companies [5, 9–12, 20] and our calculations, the most significant factors affecting the operation of sections of rotary X-shaped working bodies were determined. These are the rotor diameter – $D(X_1)$; the distance between the axes of the rotor batteries – $L(X_2)$; the distance between the rotor blades in the battery – $l(X_3)$.

Fig. 1. Combined (modular) tillage unit AMK-2.7

The listed factors were selected as varied during laboratory and field research (Fig. 2).

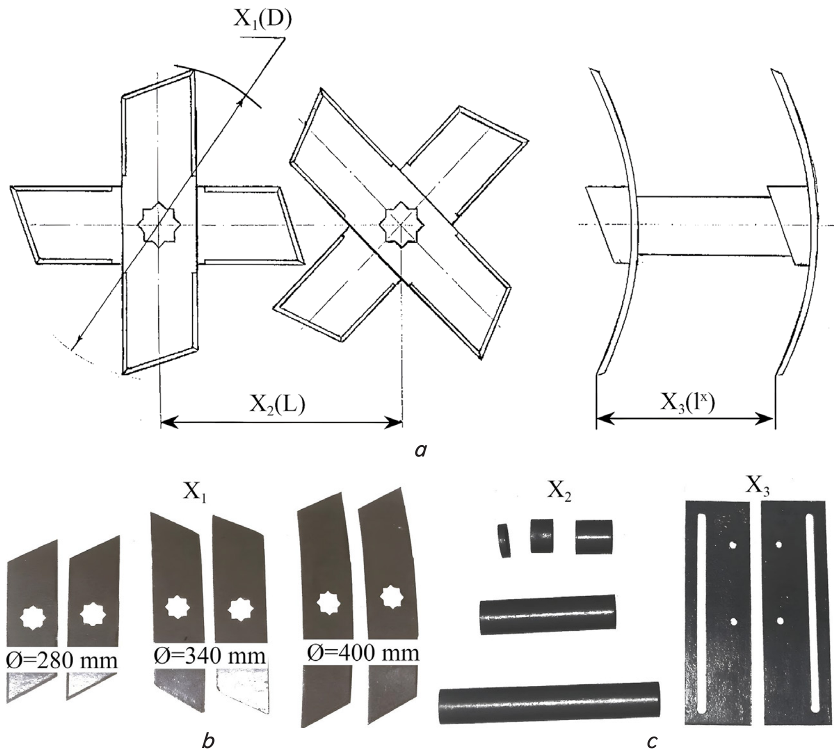

Fig. 2. Scheme of mutual arrangement and elements of X-shaped rotary working bodies: *a* — scheme of experimental installation; *b* — rotor blade plates; *c* — plates for adjusting the distance between the rotor drums

The standard D-optimal plan of the second order for three factors was used for setting up experimental studies [21]. Sampling and measurements were performed in accordance with the requirements of DSTU 2189-93 «System of labor safety standards. Agricultural mounted and trailed machines. General safety requirements».

The optimization parameter in the studies was the quality of soil loosening in a layer of 0–10 cm (the ratio of the weight of the fraction with aggregate size less than 25 mm to the total weight of the sample expressed as a percentage) and the deviation from the specified depth of soil cultivation.

To determine the soil loosening quality index, a frame was made in accordance with RD 10.4.2-89 «Testing of agricultural machinery. Machines and tools for surface soil treatment. Test program and methods» with an internal size of 0.5×0.5 m, which was superimposed on the cultivated background of the field and within which loosened soil was removed to the depth of cultivation. After that, the selected loosened soil was loaded into a box measuring 0.5×0.5×0.1 m, which had a metal bottom 2 mm thick with holes of 25 mm, which, in turn, entered a solid box measuring 0.51×0.51×0.15 m and into which, later, the fraction of soil assembly units with a size of less than 25 mm was sifted. The weight of the total soil sample and the sifted fraction were weighed separately on electronic scales VN-100-1D-3-A («Promprylad», Vinnytsia). The depth of tillage was determined using a 1.5 m long construction rule PAS-3772-1.5, which was placed on the tilled soil at an angle of about 45° to the direction of movement of the unit, lightly pressed and leveled. Measurements of the depth of processing were performed up to the level of the blade of the rule with a DICKEY-john penetrometer. The deepening was carried out up to the stop of the device nozzle in the untreated soil.

On the basis of previous studies, it was established that the influence of the considered parameters on the specific traction resistance within the limits of their change is insignificant. To do this, after each pass of the experimental setup, the depth of cultivation was measured at 27 points: 9 in the direction of movement and 3 along the width of the grip.

The factors and their levels of variation in the experiment are given in Table 1.

Table 1

Factors and levels of variation of parameters of X-shaped rotary working bodies in the experiment

Factor	Conditional designation	Level			Interval
		–1	0	+1	
Diameter of rotor blades (D), mm	X_1	280	340	400	60
The distance between the axes of the rotor batteries (L), mm	X_2	240	340	440	100
The distance between the rotor blades in the battery (l), mm	X_3	100	200	300	100

Research was conducted at three unit speeds: 2 m/s (7.2 km/h), 2.5 m/s (9.0 km/h), and 3.0 m/s (10.8 km/h). The angle of attack of the battery of knife sections was within 14–15°. The set working depth was 16 cm.

The functional purpose of the rotary working bodies as part of the combined unit is high-quality processing of the surface layer of the soil (its loosening, grinding of plant residues, and mixing them with the soil). The general appearance of X-shaped rotary working bodies, which were involved in the experiment, is shown in Fig. 3.

Conditions for field experimental research:

– soil type – southern Ukrainian chernozem (Bohdanivka village, Berdyansky district, Zaporizhia oblast, July 2021);

– soil moisture in layers 0–10 cm – 12.4±2.2 %, 10–20 cm – 13.8±1.2 %;

– soil density in layers, respectively, 1.20±0.09 g/cm^3 and 1.32±0.08 g/cm^3;

– agrophone – stubble of winter wheat. The predecessor is winter wheat.

Fig. 3. A general view of the X-shaped rotary working bodies that were used in the experiment

In order to further verify the results, at the first stage of research, two experimental units with X-shaped working bodies were manufactured based on the following structural and technological parameters: the first – the diameter of the rotor blades D=33 cm, the distance between the axes of the rotor batteries L=33 cm, the distance between blades of the rotor in the battery l=21 cm (for the movement speed of the unit V=2.5 m/s); the second – the diameter of the rotor blades D=33 cm, the distance between the axes of the rotor batteries L=35 cm, the distance between the rotor blades in the battery l=11 cm (for the unit movement speed V=3–3.5 m/s). The evaluation was carried out in terms of stability of the movement of the working bodies at the depth $h\pm\sigma$, cm (where h is the average depth of cultivation, and σ is the root mean square deviation of the depth of soil cultivation).

5. Results of investigating the parameters of the section of the X-shaped rotary working bodies for loosening the soil

5. 1. Influence of the speed of movement of the unit and the parameters of the X-shaped rotary working bodies on the quality of loosening the soil

After conducting the experiment and processing the experimental data, regression equations were built, on the basis of which the parameters of the rotary working bodies were optimized for different speeds of movement of the unit and the actual working (it was during the experiment) depth of cultivation $h\approx 14\pm 2$ cm.

The regression equation for determining the quality of soil loosening in the 0–10 cm layer in coded form is as follows:

– at a unit speed of 2 m/s:

$$Y_2 = 72.52 - 0.14\cdot X_1 - 0.89\cdot X_2 - 0.1\cdot X_3 - 0.975\cdot X_1\cdot X_2 - 0.775\cdot X_1\cdot X_3 + 0.025\cdot X_2\cdot X_3 - 7.1\cdot X_1^2 - 2.05\cdot X_2^2 - 1.2\cdot X_3^2 - 1.05\cdot X_1\cdot X_2\cdot X_3; \quad (1)$$

– at a unit speed of 2.5 m/s:

$$Y_{2.5} = 76.51 - 0.2\cdot X_1 - 0.8\cdot X_2 - 0.21\cdot X_3 - 0.875\cdot X_1\cdot X_2 - 0.8\cdot X_1\cdot X_3 + 0.7\cdot X_2\cdot X_3 - 6.71\cdot X_1^2 - 3.01\cdot X_2^2 - 0.46\cdot X_3^2 - 0.925\cdot X_1\cdot X_2\cdot X_3; \quad (2)$$

– at the speed of the unit 3 m/s:

$$Y_3 = 74.3 - 0.337 \cdot X_1 - 0.193 \cdot X_2 - 0.817 \cdot X_3 - 1.046 \cdot X_1 \cdot X_2 - 0.071 \cdot X_1 \cdot X_3 + 0.471 \cdot X_2 \cdot X_3 - 6.502 \cdot X_1^2 - 1.852 \cdot X_2^2 - 0.302 \cdot X_3^2 + 0.196 \cdot X_1 \cdot X_2 \cdot X_3. \quad (3)$$

Graphical interpretation of the influence of the studied parameters on the quality of crushing at a unit speed of 2.5 m/s is shown in Fig. 4–6.

Results of optimizing the regression equations at three speeds, provided $Y \to$max, are given in Table 2.

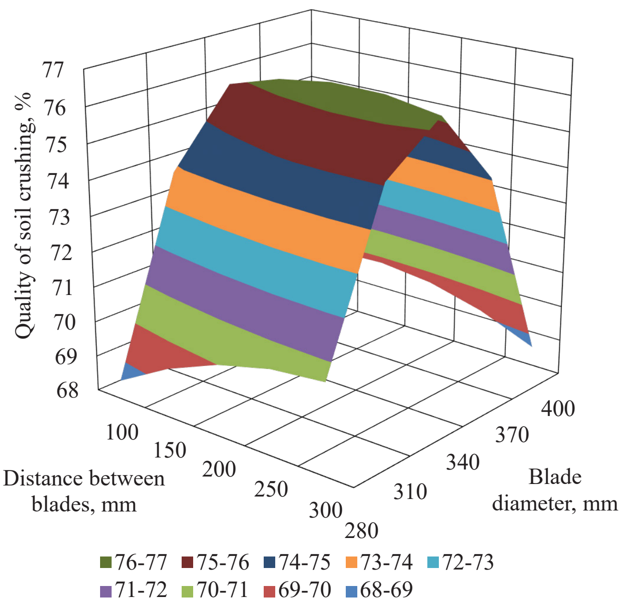

Fig. 4. Influence of the distance between the rotor blades and the diameter of the blades on the quality of soil crushing in a layer of 0–10 cm with a distance between the axes of the rotor batteries of 340 mm

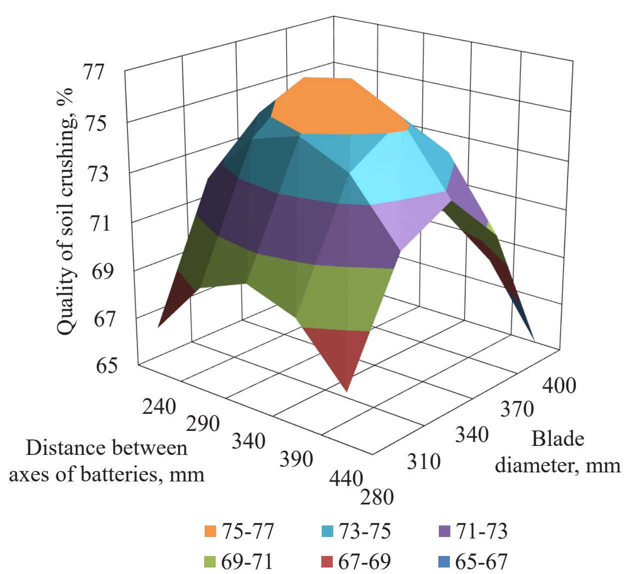

Fig. 5. Influence of the distance between the axes of the rotor batteries and the diameter of the blades on the quality of soil crushing in a layer of 0–10 cm with a distance between the rotor blades of 200 mm

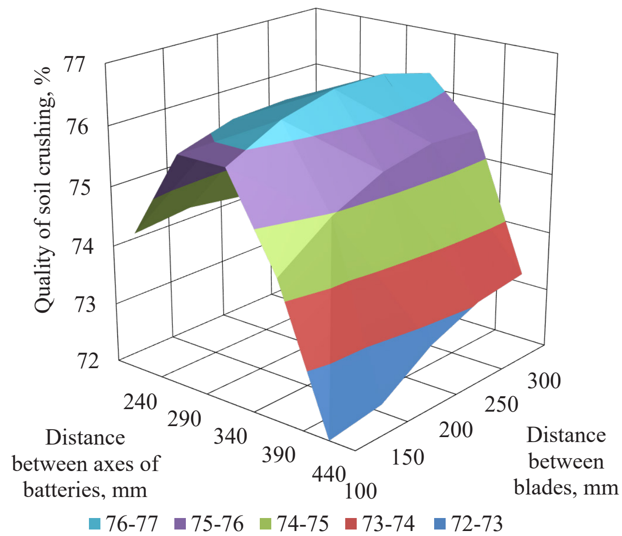

Fig. 6. Influence of the distance between the axes of the rotor batteries and the distance between the rotor blades on the quality of soil crushing in a layer of 0–10 cm with a blade diameter of 340 mm

Table 2

Optimum values of parameters of the section of rotary working bodies according to the quality of loosening the soil

Factor	Optimal values at movement speed, mm		
	2 m/s	2.5 m/s	3 m/s
Rotor knife diameter – $D(X_1)$, mm	335.9	331.2	330.1
Distance between rotor battery axes – $L(X_2)$, mm	316.4	325.7	346.8
Distance between rotor blades in the battery – $l(X_3)$, mm	195.6	211.3	106.1
Quality of soil loosening in the layer 0–10 cm, %	72.52	76.51	74.3

Our results of optimizing the section sizes of rotary working bodies were used during the manufacture of an experimental sample of a modular combined unit for surface and pre-sowing soil cultivation.

The operating speed range of the combined unit at which it can be installed was also taken into account. For example, on the AMK-2.7 combined unit, which is being designed for the above-mentioned tasks, and for which the parameters must be selected for a speed of at least 2.1 m/s based on the operating conditions of the S-shaped racks.

5. 2. Influence of the speed of movement of the unit on the stability of the movement of X-shaped rotary working bodies in terms of the depth of cultivation

The efficiency of the work of the studied working bodies was determined by the stability of the course of the working bodies in terms of the depth of processing («excavation» of working bodies under load). Our results of the studies are given in Table 3 and demonstrated graphically in Fig. 7.

Our results are indirectly characterized by the traction resistance of the unit. It is important to note that with a significant increase in the intensity of the impact on the soil environment, which occurs with an increase in the speed of movement of working bodies, the compaction of individual separated soil assembly units increases significantly. This is especially evident on dark chestnut heavy loamy soils and southern Ukrainian chernozems. At the same time, degradation processes are started in the soil environment, and therefore, on such soils, it is expedient to increase productivity by increasing the width of the unit's capture. Degradation processes are not observed on light, medium-loamy, or structureless soils, and increasing the speed of movement of working bodies will not harm.

Table 3

Results of determining the stability of the movement of working bodies in terms of the depth of processing

Unit speed, m/s	Working depth, cm	Standard deviation of the working depth, cm	Quality of soil loosening in the layer 0–10 cm, %
2.5	13.1	1.21	79.2±1.9
3	12.6	1.07	84.1±1.4
3.5	11.9	0.63	84.6±0.9

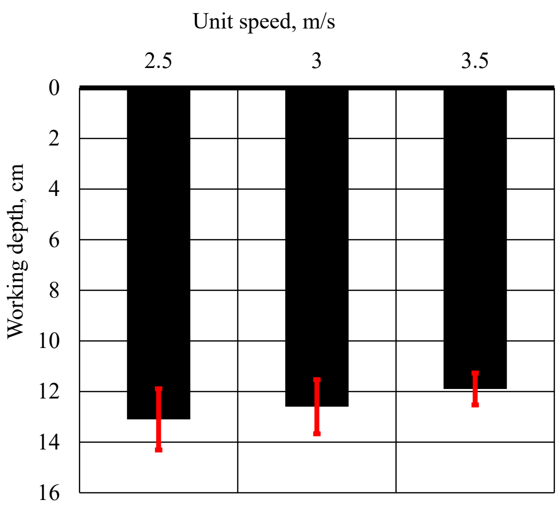

Fig. 7. Stability of movement of X-shaped working bodies in terms of the depth of processing

6. Discussion of results related to determining the influence of the parameters of the section of X-shaped rotary working bodies on soil loosening

Our results regarding the influence of the section parameters of the X-shaped rotary working bodies on soil loosening ensure the improvement of quality of the soil environment by establishing rational structural and technological parameters for the X-shaped working bodies.

Analysis reveals that with an increase in the diameter of the blades, the quality of soil crushing increases up to the specified diameter for a given speed. This can be explained by the fact that as the diameter increases, the distance between the blades at the time of their penetration into the soil medium increases. With smaller diameters of the blades, when they enter the soil, there is «tamping» of plant remains under the rotor and they partially roll in front of the drums, which worsens the crushing conditions. As the diameter increases, the crushed remains pass under the drums, and the soil deformation zones are rolled over with separate blades, that is, there is a so-called «unblocked cutting» mode, and the crushing quality indicators are at their maximum. With a further increase in diameter, each knife can perform a separate entry into the soil without overlapping the deformation zones, working under the «blocked loosening» mode, which leads to a decrease in the quality of soil crushing. The same can be explained by the influence of the distance between the blades on the quality indicator of soil crumbling: for small knife diameters, with an increase in the distance, the process of soil crumbling is unblocked, which is blocked by partially crushed plant residues and the remains of the root system of plants raised to the surface. For larger knife diameters, on the contrary, a smaller distance between the blades gives a better quality of soil crushing, in this case, the remains are pushed between the blades and do not prevent the blades from entering the soil and loosening it, but with an increase in the distance between the blades, the deformation zones with the blades no longer overlap and the quality of crushing of the soil decreases (Fig. 4).

At shorter distances between the axes of the batteries, the separated elements of the soil environment with plant remains are partially thrown over the second rotor or pushed between the blades and are not additionally crushed. At optimal values of the distance between the axes, separate elements of the separated soil fall on the rotor blades of the second drum in the zone of its active action, are partially crushed, and then return to the surface in the zone where they are pinched by this drum at the moment when the blades enter the soil («pinch» zone). Thus, the quality of soil crushing increases. An increase in the distance between the axes of the batteries reduces the probability of the separated elements of the soil environment falling into the active zone of the blades of the second drum, and the quality of soil crushing decreases (Fig. 5).

The setting of the distance between the blades is significantly influenced by the level at which the diameter of the knife, the distance between the axes of the batteries, and the speed of the tool are fixed. For a small distance between the blades, the conditions for the passage of the crushed soil-plant mixture through the first drum are not provided, which significantly worsens the conditions for loosening the soil and can stop the technological process altogether. When the distance between the blades increases, the conditions for unblocked loosening of the soil by individual rotor blades worsen, which reduces loosening of the soil medium. It is more expedient to place the blades as close as possible while ensuring the passage of the crushed soil-plant mixture. Research has shown that increasing the speed significantly improves the passage of the plant-soil mass through the inter-knife space (Fig. 6).

It was also established that the optimal value of the diameter of the rotor blade, depending on the tool speed, decreases from 335.9 mm at V=2 m/s to 330.1 mm at V=3 m/s. As the speed increases, the resistance of the rotor blade, which as part of the section battery has an angle of attack of 15° to the direction of movement, increases and the component of the resistance force tries to push the blades out of the ground. The larger the diameter of the rotor, the greater the pushing force. Decreasing the depth of soil cultivation leads to incomplete loosening of the cultivated layer and, as a result, the quality of crushing decreases. The distance between the axes of the rotor batteries increases from 316.4 mm to 30.4 mm with an increase in the speed of movement of the unit from 2 m/s to 3 m/s. Based on the fact that the elements of the soil separated by the blades of the rotor of the first row move due to kinetic energy and according to the ideal schedule should fall under the blades of the second row in the «clamping zone»: «knife» – «separated soil element» – «soil surface», rather than moving outside of this zone. That is, an increase in the speed of movement leads to an increase in the distance between the axes of the disk batteries in order to provide this «clamping zone» with additional grinding of separated elements. The distance between the blades of the rotor in batteries also depends on the speed of movement of the tool in relation to the quality of soil crushing. As the speed increases, the rotor blade spacing initially increases from 195.6 mm (2 m/s) to 211.3 mm (2.5 m/s), but further decreases significantly to 106.1 mm for a speed of 3 m/s. It is difficult to clearly explain this, but it can be predicted that the plant residues clog the distance between the blades in the battery at a certain speed. At the same time, the blades only pierce the soil environment. Slots are formed in the soil, and the separation of soil elements is blocked by compacted plant residues in the battery. With an increase in speed, this compacted mass of plant residues is pushed out, which makes it possible to reduce the distance between the blades in the battery and significantly improve the quality of soil crushing (Table 2).

As for the data from studies on the stability of the movement in terms of the depth of processing with X-shaped working bodies depending on the speed of movement, the root mean square deviation decreases with the increase of the speed of movement (Fig. 7). This means that the working bodies more stably perform the technological process according to the fixed depth of processing to which they have penetrated. This is explained by the fact that with the increase in speed, the transfer component of the speed of movement in relation to the rotational one increases and such a phenomenon as slipping becomes more pronounced. In this way, the knife element, in part, for a very short period of time (≈0.1–0.3 s) begins to work as a «passive» disintegrator without rotation. This improves the uniformity and quality of loosening the soil and stability of the blades in depth, but the energy consumption will increase significantly. Therefore, the stability of the movement of the working bodies in terms of the depth of cultivation decreases with an increase in the movement speed of the unit. At a unit movement speed of 2.5 m/s, the average depth of soil cultivation is set at 13.1 cm, at a unit movement speed of 3 m/s – 12.6 cm, and at a unit movement speed of 3.5 m/s – at 11.9 cm. This indicates a slight deviation in the stability of the movement of the working bodies in terms of the depth of cultivation when the speed of movement changes. In addition, at a movement speed of the unit of 2.5 m/s, the root mean square deviation of the soil tillage depth is 1.21 cm, at a movement speed of the unit of 3 m/s – 1.07 cm, and at a movement speed of the unit of 3.5 m/s – 0.63 cm. This indicates a significant influence of the deviation of the tillage depth depending on the speed of movement and requires consideration of this phenomenon when equipping tillage units.

The uniqueness of studies on the loosening and mixing of soil with plant residues is determined by conducting them in a wide range of basic parameters of working bodies of the specified type at technologically fixed speeds of movement and depth of cultivation. Based on the results of the study, regression equations were built for the quality indicators of the tool. This allows us to argue about the superiority of our research compared to similar ones [4, 7], in which the systemic influence of parameters on performance indicators was not considered.

Our solutions make it possible to determine the main structural and technological parameters of X-shaped working bodies, which will make it possible to design highly efficient combined tillage units. This is explained by the fact that the X-shaped working bodies provide preliminary soil treatment, which ensures the conditions for the quality work of the following working bodies.

It is necessary to take into account that X-shaped working bodies during the execution of the technological process, depending on the type of soil, its humidity, and the speed of movement, have the property of «floating» in relation to the set depth of cultivation. According to the research results, this phenomenon is weakly expressed in the range from 2 m/s to 3 m/s. But an increase in speed of more than 3 m/s on wet overcompacted loams significantly reduced the working depth of cultivation. This limits the range of use of the specified working bodies by speed as autonomous tools or requires additional loading of the section of the X-shaped working bodies, which is not rational. As a part of combined tools at a speed of more than 3 m/s, its weight will probably restrain the excavation of the grinding sections. This will lead to an increase in pressure on the surface of the blades, their sticking with the soil, and a partial increase in the traction resistance of the tool as a whole. Thus, this leads to deterioration of the conditions of rotation of the rotor and, as a result, reduces the quality of soil crushing. Reducing the diameter of the rotor blade improves its rotation (an analogy can be drawn with spherical disks with an angle of attack of up to 20°). At the same time, the intensity of impact on the soil increases (the number of knife elements entering the soil) and, thus, the quality of soil crushing improves.

Among the shortcomings of our research is having conducted it under specific soil and climatic conditions; they are zonal in nature, and our results are limited to the conditions of conducting the experiment in terms of humidity, initial layer-by-layer density of the soil, and weediness of the backgrounds. In addition, the research was carried out within the defined limits for the speed of interaction with the soil. The width and thickness of the knife plate was adopted based on the condition for enabling reliable operation of the structure. The angle of attack of the battery of knife sections was fixed and taken at the level of 14–15°. The radius of curvature of the plate was chosen at the level of 610 mm based on the analysis of the parameters of similar designs of tillage bodies. The background of the research is winter wheat turf with a height of 8–14 cm.

Research results could be used in the design of single-operation machines with X-shaped working bodies for work under certain soil and climatic conditions.

7. Conclusions

1. It was established that the optimal values of the parameters of the section of the X-shaped rotary working bodies for the quality of loosening the soil in a layer of 0–10 cm at a depth of cultivation of 14±2 cm depend on the speed of the unit. Thus, at a speed of movement of the unit of 2 m/s, the optimal value of the diameter of the rotor blade is 335.9 mm, the distance between the axes of the rotor batteries is 316.4 mm, and the distance between the rotor blades in the battery is 195.6 mm. At a unit movement speed of 2.5 m/s, the optimal values of these parameters are 331.2, 325.7, and 211.3 mm, respectively, and at a unit movement speed of 3 m/s – 330.1, 346.8, and 106, 1 mm.

2. It was established that stability of the movement of the working bodies in terms of the root-mean-square deviation of the working depth increases with the increase in the speed of the unit. Thus, at a movement speed of the unit of 2.5 m/s, the root mean square deviation of the soil tillage depth is

1.21 cm, at a movement speed of the unit of 3 m/s – 1.07 cm, and at a movement speed of the unit of 3.5 m/s – 0 .63 cm. It was also established that stability of the movement of the working bodies in terms of the depth of cultivation decreases with an increase in the speed of movement of the unit. Thus, at a movement speed of the unit of 2.5 m/s, the average soil tillage depth is set at the level of 13.1 cm, at a movement speed of the unit of 3 m/s – 12.6 cm, and at a movement speed of the unit of 3.5 m/s – at the level of 11.9 cm.

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, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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