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The optimisation of the cylinder-spiral soil-cultivating roller

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Abstract. Designed cylinder-tillage spiral skating rink with spiral work items, which form a fine lumpy structure of the sowing layer of soil with grain size corresponding to agrotechnical requirements, while helping the soil surface, mulching the top layer of soil over the seeds, seal the depth of their placement, providing the required contact of seeds with soil is necessary to ensure the uniformity of germination. At the theoretical level, it is determined that an increase in the pinching angle leads to an increase in the size of the hollow smooth pipe of the roller. This occurs while increasing the depth of deformation of the layer of crushed soil and the radius of the clump of soil. However, a change in the radius of a hollow smooth roller of more than 0.3 m does not lead to a slight increase in the pinching angle. Therefore, increasing the radius of the hollow smooth roller over 0.3 m is not rational, as it will increase the metal content of the structure. After analyzing the obtained mathematical models of the soil treatment process with a roller, we optimized the parameters of a cylindrical-spiral roller: speed of 11 km/h, mass of ballasting loads of 100 kg, step of the spiral turn of 40 mm, and the departure of the spiral screw of 35 mm. These modes ensure the formation of a qualitatively compacted soil layer in the zone of planting seeds of agricultural crops, which is confirmed by the maximum value of the processing quality criterion for matching the density of the soil after rolling with a cylindrical-spiral roller CCS = 0.98 (while the density of the sown layer addition 1185...1215 kg/m^3), which fully satisfies the agrotechnical optimum. The yield of barley of the Nutans-553 variety became higher after the use of an innovative cylindrical-spiral roller by 6.4 % and 9.3 %, respectively, of the yield after the impact of serial KKSh rollers and ring rollers of the seeding machine. In the course of evaluating the metal consumption of structures of the innovative cylindrical-spiral roller and the ring-spur roller, a difference of 70% per unit width of the grip was revealed.

In the system of agricultural cultivation operations, producers of crop products face the negative aspect: the germination of seeds of cultivated plants in real field conditions is worse than that determined in laboratory conditions. The elimination of this discrepancy remains relevant [1]. This negative phenomenon significantly reduces productivity and, as a result, leads to a loss of income from production activities. One of the well-established factors of this difference in seed germination is surface treatment of the soil during sowing

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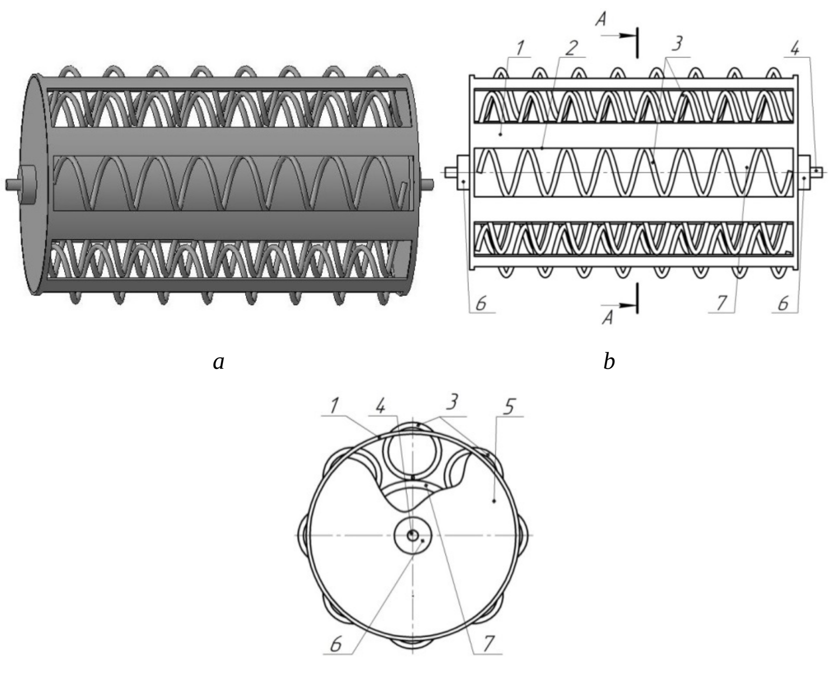
for the purpose of compaction and structuring. After treating the soil with rolling tools, the necessary compaction of the seed layer and the rise of moisture from the lower layers due to the formation of a capillary structure is provided for agricultural seeds. Rolling agricultural tools should grind large soil aggregates and smooth the microrelief of the field [2]. Consequently, the operation of post-seeding compaction and structuring of the soil layer in the area where the seeds of agricultural crops are located becomes an important aspect of agricultural cultivation, ensuring the uniformity of seedlings.

The above allows us to formulate the purpose of the study - to improve the quality of post-sowing compaction and structuring of the soil layer in the zone of seed location on the basis of the development of a cylindrical-spiral roller, which ensures the achievement of agrotechnical indicators of the process and increase the yield of agricultural crops.

When inventing and modeling agromachines, it is possible to ensure high efficiency of their operation on the basis of mechanical and technological justification of new principles and technological order of interaction of working bodies of agricultural tools with the soil, based on the combination of heterogeneous effects and deformations of the processed medium to ensure its required technological properties [3].

Based on the analysis of the designs of rotary loosening and compacting working bodies of agricultural tools, a cylindrical-spiral tillage roller (figure 1) made of a hollow smooth pipe 1 was developed. Along the surface of the pipe in the longitudinal direction with an equal step, holes 2 are made along the entire length of the hollow smooth pipe 1. In the rectangular holes 2, spiral screws 3 are installed parallel to the axis of its rotation.



a - 3D-model of the rink; *b* - front view; *c* - side view

Fig. 1. Cylindrical-spiral tillage roller.

The width of the holes 2 is made less than the diameter of the spiral screws 3. The distance between the turns of the spiral screws 3 is made less than or equal to the agrotechnically set maximum size of soil lumps. At the ends of the hollow smooth pipe 1, disks 5 are located on the axis 4, in the center of which bearing supports 6, are installed on the outer sides. A hollow cylinder 7 is installed coaxially Inside the hollow smooth pipe 1. To ensure the fixed position of the spiral screws 3 in the holes 2, the diameter of the hollow cylinder 7 is selected so that its outer cylindrical surface contacts the outer surfaces of the spiral screws 3. The ends of the hollow cylinder 7 touch the inner surface of the disks 5.

The working process of the roller is as follows: supports 6 connected to the frame are connected to the hitch with the seeder. Rolling over the surface of the soil, large soil aggregates are destroyed by spiral screws 3 and the edges of holes 2. In this case, spiral screws sinking into the soil affect its aggregates, creating a strain of tension-compression. This principle of elastic effects on lumps intensifies the process of their crumbling. In addition, spiral screws 3 seal the subsurface soil layer. At this point, the part is deformed lumps falls into the internal cavity bounded by a hollow smooth tube 1 outer surface of the hollow cylinder 7, crumble, hitting the turns of spiral screw 3. The outer cylindrical surface of the hollow smooth tube 1 between the spiral screws 3 when rolling tillage rink, creating stress state in the contact zone with soil, condenses, smoothes the surface and destroys large clods of soil, pressing them into the top layer of the soil.

Spiral screws form a fine-lumped structure of the sown soil layer with the size of the fraction corresponding to agrotechnical requirements. In addition, spiral screws align the soil surface, mulch the top layer of soil over the seeds, and seal the soil at the depth of their embedding, ensuring the required contact of seeds with the soil, which is necessary to ensure uniformity of seedlings. In addition, the presence of spiral screws and edges of holes in the hollow smooth pipe, located perpendicular to the direction of movement, prevents the cylindrical surface of the smooth hollow pipe from slipping, which eliminates the formation of cracks on the soil surface and, as a result, reduces the intensity of moisture evaporation from the soil layers, in which the root system of cultivated plants is formed. Thus, the above-mentioned distinctive features of the tillage roller contribute to improving the quality of soil compaction.

Pinching of soil clumps occurs between the outer surface of the hollow smooth pipe and the soil. At the same time, there should be no pushing of soil lumps forward in front of the roller under the influence of the resultant force of surface pressure, which will lead to shifting of the soil layers and the formation of cracks. This force is oriented towards the solution of the surfaces and is balanced by the forces of friction, adhesion and external forces. The maximum value of the angle of pinching χ of soil aggregates by the roller, at which there is a negative phenomenon of pushing out large soil aggregates, is due to the sum of the angles of friction of lumps on the surface of a hollow smooth pipe φ_1 and soil φ_2. The main factor affecting the size of the pinching angle is the radius and material of the hollow smooth pipe. Therefore, to eliminate the shift in the ground before the hollow smooth tube of the rink and provide a guaranteed condition of crushing of soil aggregates is necessary and sufficient fulfillment of the inequality $\chi \leq (\varphi_1 + \varphi_2)$, that is, the angle between the tangent to the surfaces defined by the sum of the angles of friction φ_1 and φ_2 were less than or at least equal to this amount (figure 2,*a*). If this condition is met, the soil lump is not pushed out and it does not shift, resulting in displacement of the surface layers of the soil. To simplify calculations, we assume that the cross section of soil lumps represents the shape of a circle. We accept parameter designations: the radius of a hollow smooth tube of a cylindrical-spiral roller *R*, the radius of a clump of soil *r*.

Imagine the equation of the circle in polar coordinates, we get:

$$\rho = R. \tag{1}$$

Write equation (1) in a rectangular coordinate system:

$$\begin{cases} x = Rcos\varphi \\ y = Rcos\varphi \end{cases}, \tag{2}$$

where x and y - are the coordinates of the tangent at the current time, m; φ - is the second polar coordinate, counted from the first polar coordinate in our case from the axis *Ox* to the segment *OM*, deg.

Having constructed a tangent straight line to the circle of the soil clod passing through the point of contact of the clod with the soil *A*, we write the tangent equation [4]:

$$y = y_A + y_x^{/}(x - x_A), \tag{3}$$

where y_A and x_A - instant coordinates of a point *A*, m.

$$y_x^{/} = y_\varphi^{/}/x_\varphi^{/} = (Rcos\varphi)/(Rsin\varphi) = -ctg\varphi. \tag{4}$$

From expression (4), we define the tangent line parameter [5]:

$$k = y_x^{/} = -ctg\varphi. \tag{5}$$

Taking into account the expression (5) and as a result of mathematical transformations, we determine the distance from point *O* to point *M*:

$$OM = H = (y_A + x_A ctg\varphi + h)/(\sqrt{1 + ctg^2\varphi}) = x_A cos\varphi + (y_A + h)sin\varphi. \tag{6}$$

The resulting expression (6) characterizes the dependence of the distance *OM* on the angle φ, taking into account the existing deformation of the soil under the soil clump h. On the other hand, the *OM* distance can be found as follows:

$$OM = H = (R + r)cos\chi + r. \tag{7}$$

Then the parameter cos χ:

$$cos\chi = [x_A cos\varphi + (y_A + h)sin\varphi - r]/(R + r). \tag{8}$$

Therefore, in order to avoid shifting the soil in front of the hollow smooth pipe of the roller and to ensure the condition of guaranteed pinching of soil aggregates, it is necessary and sufficient to perform the inequality:

$$\chi \leq \arccos\{[x_A cos\varphi + (y_A + h)sin\varphi - r]/(R + r)\}. \tag{9}$$

The interaction of the roller with the soil clump causes the appearance of the force R_1, and the reaction of the soil R_2 from the action of the clump on it (figure 2, *b*). These forces can be decomposed into the normal components F_{n1} and F_{n2} and the friction forces F_{f1} and F_{f2}, respectively. If the final value of the projections of friction forces on the x-axis is greater than the final pushing forces in the projection on the same axis, the soil aggregate will be delayed between the outer surface of the hollow smooth pipe of the roller and the soil surface and crushed, since the mass of the roller is much larger than the mass of the soil lump. Let's analyze the requirements under which a hollow smooth pipe of a roller interacts with a lump of soil.

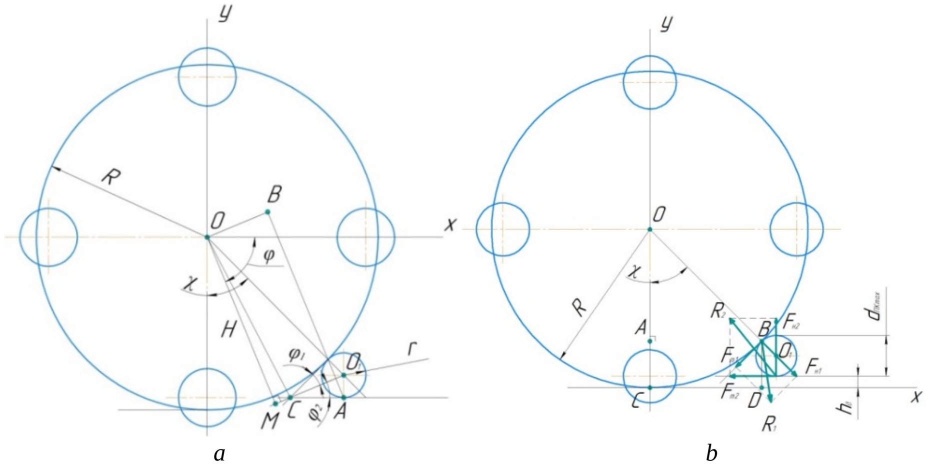


Fig. 2. To determination of the pinching angle (*a*) and radius of the cylindrical-spiral roller (*b*).

For the purpose of simplification, we assume that the hollow smooth pipe of the roller moves, rolling over the surface of the soil, and there is no slippage. The soil surface is solid and does not experience deformation. The soil lump is a ball with the main parameter - the diameter of $d_{sc\ max}$, which is due to the agrotechnical established and acceptable size of large fractions. Let's make a system of equations for projections of all forces on the *x* and *y* axes:

$$\sum F_{kx} = F_{n1}\sin\chi - F_{f1}\cos\chi - F_{f2} = 0\,, \tag{10}$$

$$\sum F_{ky} = F_{n2} - F_{n1}\cos\chi - F_{f1}\sin\chi = 0\,. \tag{11}$$

After appropriate mathematical transformations and taking into account $F_{f1} = \mu_1 F_{n1}$ and $F_{f2} = \mu_2 F_{n2}$, where μ_1 and μ_2 – the coefficients of friction of the hollow masonry pipe of the roller on the soil and the soil clump on the soil, respectively, were obtained:

$$\chi \ge \operatorname{arctg}[(\mu_1 + \mu_2)/(1 - \mu_1\mu_2)]\,. \tag{12}$$

Then the minimum design diameter of the cylindrical-spiral roller d_{min} can be determined depending on the height of the deformation layer *h*, the agrotechnically established and permissible size of large fractions $d_{sc\max}$ and the optimal angle χ.

Distance from the surface of the deformed soil under the clump to the point *B* of contact with the hollow smooth pipe of the roller and the surface of the clod of soil:

$$BD = h + 0{,}5 d_{sc\max}[1 + \cos\chi]. \tag{13}$$

Distance

$$AC = BD = 0{,}5 d_{min} - 0{,}5 d_{min}\cos\chi = 0{,}5 d_{min}[1 - \cos\chi]. \tag{14}$$

Since *AC* = *BD*, and taking into account the expression (12), the minimum diameter of the cylinder-spiral roller

$$d_{min} = \frac{h + 0{,}5 d_{sc\max}\langle 1 + \cos\{\operatorname{arctg}[(\mu_1 + \mu_2)/(1 - \mu_1\mu_2)]\}\rangle}{1 - \cos\{\operatorname{arctg}[(\mu_1 + \mu_2)/(1 - \mu_1\mu_2)]\}}\,. \tag{15}$$

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Mathematical transformations of the expression (15) allow us to obtain a dependence for determining the minimum radius of a cylindrical-spiral roller, taking into account the angle of pinching of the soil lump and the geometric parameters of the lumps located on the soil surface:

$$R_{min} = [h + r_{max}(1 + \cos\chi)]/(1 - \cos\chi). \tag{16}$$

The graphic dependence (16) of the radius of the hollow smooth pipe of the roller R relative to the angle of pinching χ for different radii of the soil clump r is shown in figure 3.

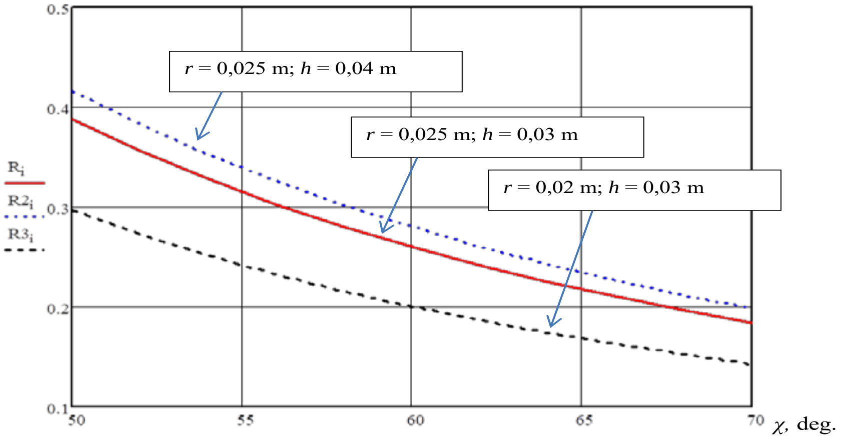


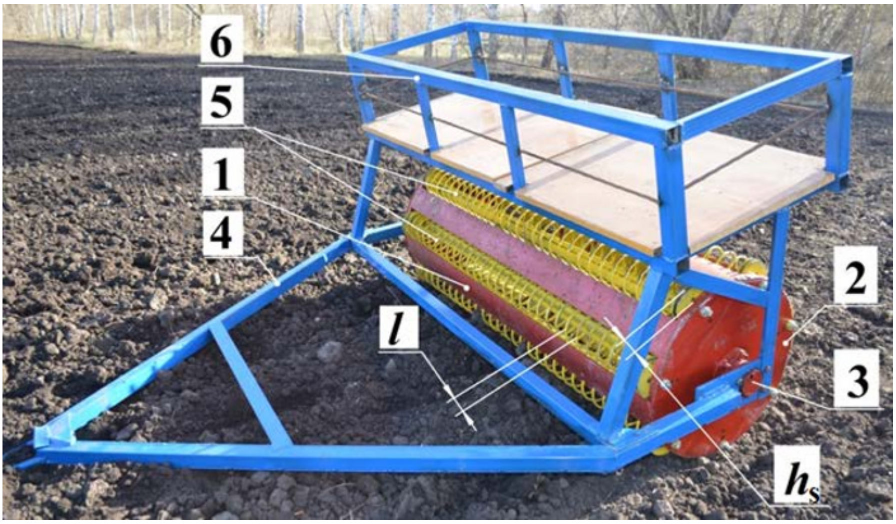
Fig. 3. The dependence of the radius of a smooth hollow pipe of the roller R on the angle of pinching χ for different radii of lumps r and the values of soil deformation h.

Thus, formula (16) establishes the dependence of the minimum diameter hollow smooth tube of cylinder-spiral rink to the height of a deformable soil layer, a grotehnicheskij installed and the allowable size of the coarse particles, the friction coefficient between the ice rink and tillage of the clod of soil, depending on the material, hollow smooth tube roller.

The theoretical research shows that increasing the angle of pinching requires increasing the size of the hollow smooth pipe of the roller. This occurs while increasing the depth of deformation of the layer of crushed soil and the radius of the clump of soil. However, a change in the radius of a hollow smooth roller pipe of more than 0.3 m does not lead to a significant increase in the pinching angle.

For the production of an experimental model of the developed agricultural equipment, taking into account theoretical research, the diameter of a hollow smooth pipe of 0.265 m was taken from the standard range of pipe diameters according to GOST 10704-91. The model of a cylindrical-spiral roller (figure 4) is made of a hollow smooth pipe 1, with disks 2 installed at the ends of it. On the surface of the pipe 1, holes are made in which spiral-screw working bodies 5 are installed. These working elements provide a finely structured topsoil layer that prevents intensive evaporation of valuable soil moisture. A special feature of the design is the ability to change the departure of spiral-screw working bodies and the step of their turn. Such adjustments are provided to optimize these parameters. To regulate the pressure on the soil, there is a mechanism for attaching balancing weights 6.

The cylindrical-spiral roller during operation must form a qualitatively compacted to the optimal value and structured small-aggregate topsoil. Therefore, for a comprehensive assessment of the process under study, we need a criterion that can reliably characterize the process under study and link the factors affecting it to the model [6]. As such, the criterion compliance of standard (CCS) has been developed. CCS is used to determine the quality of soil rolling by comparing the density indicators after its treatment with a cylindrical-spiral roller to the reference values of agricultural requirements (ρ_{opt} = 1200 kg/m^3). CCS is easy to calculate for any rolling agricultural tools, as it is a universal and visual indicator.



h_s – departure of spiral screws relative to the surface of a smooth hollow pipe; l – spiral screw turn step; 1 - hollow smooth pipe; 2 - disk; 3 - bearing supports; 4 - coupling; 5 - spiral screws; 6 - mechanism for securing ballasting loads;

Fig. 4. Experimental model of a cylindrical-spiral roller.

CCS is calculated using the equation:

$$CCS = 1 - (|\rho_{opt} - \rho_e|/\rho_{opt}) \tag{17}$$

where ρ_{opt} - is the soil density at the depth of seeding in accordance with agrotechnically established requirements for the cultivation of a particular crop, kg /m^3; ρ_e - is the experimentally obtained values of soil density, kg/m^3.

The soil density at the depth of seeding of $\rho_{опт}$ based on the analysis of agricultural requirements was selected 1200 kg/m^3, which corresponds to the optimal soil density for sowing grain crops. In full compliance with the soil density at the depth of the seed location agrotechnical optimal value CCS = 1.

Various factors affect the rolling of the soil with the proposed cylindrical-spiral roller. As controlled factors of the process, we chose: v (x_1) – speed of movement of the cylindrical-spiral roller, km/h; m (x_2) - mass of ballasting cargo, kg; h_s (x_3) - departure of the spiral-screw working body, mm; l (x_4) – step of the spiral-screw working body, mm. Based on the analysis of well-known experiments on rolling the soil, conclusions from search studies, existing theoretical data, as well as on the basis of the design features of the developed roller, the ranges of changes in factors were selected. Levels and intervals of changes in factors: the speed of the tillage roller varied from 7 km /h to 15 km/h with an interval of variation of 4 km/h, the pitch of the spiral screw – from 30 to 60 mm with an interval of 15 mm; the weight of ballasting loads-from 0 to 300 kg with an interval of 150 kg; the departure of the spiral screw relative to the surface of a hollow smooth pipe - from 0 to 50 mm with an interval of 25 mm.

As a function approximating the optimization criterion and independent factors, we can use an expression that is a formatted simulation of the process of compaction and structuring of the surface seed layer of the soil developed by a cylindrical-spiral roller [7]. To form a mathematical model, it is sufficient to use the following regularity [8]:

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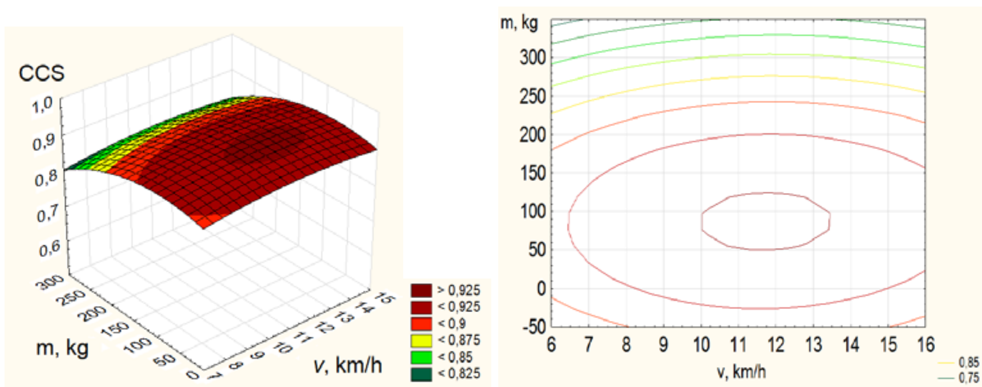
$$y = b_0 + \sum_{i=0}^{n} b_i x_i + \sum_{i=1}^{n\ 1} \sum_{i=j=1}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_i^2 , \tag{18}$$

where y - is the optimized value; x_i (i = 1, 2…n) – parameters that affect the optimized value y after conversion to encoded values; b_i, b_{ij}, b_{ii} –coefficients that determine the correlation component of the model.

As a result of a multi-factor experiment with a possible combination of factor values and processing of the array of data obtained, mathematical models were obtained describing the process of forming a compacted soil layer by a cylindrical-spiral roller, showing the influence of independent factors on CCS. A second-order polynomial describing the influence of m and v on CCS:

$$CCS = 0{,}7758 + 0{,}0234v + 0{,}0004m - 0{,}001v^2 + 0{,}00000257vm - 0{,}0000021m^2, \tag{19}$$

3D-graphs and level line maps are constructed that characterize the interaction of independent factors m and v, as well as their joint influence on CCS (figure 5).



a *b*

Fig. 5. 3D-graphs (*a*) and level line maps (*b*).

Constructing and analysing models of the densification process and structure of the sowing layer of soil developed cylinder-spiral roller, has determined that the maximum value of CCS after exposure of cylinder-spiral roller amounted to 0.98 (corresponding to the density of the soil ρ = 1185...1215 kg/m^3), which fully meets the agronomic optimum and is achieved when the rate of cylinder-spiral rink 11 km/h, the mass of ballasting of cargo of 100 kg, step spiral of the working body 40 mm, the radius of the spiral screw of 35 mm.

In the subsequent testing of the cylindrical-spiral roller took place in a peasant farm. It was found that the yield of spring barley of the Nutans-553 variety (figure 6) after exposure to a cylindrical-spiral roller for an average of three years exceeded by 6.4% and 9.3%, respectively, the yield of this crop after rolling with a ring-spur roller 3KKSh-6 and ring rollers of the SZ-5.4 seeder.

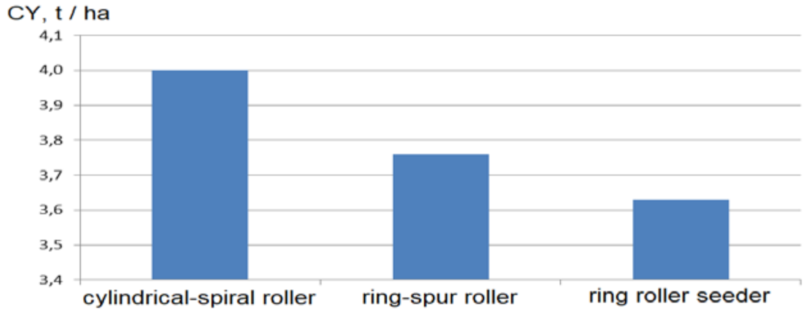


Fig. 6. Yield of spring barley

Thus, the study theoretically determined that by increasing the depth of deformation of the surface layer of soil rolled down and the size of the lump of soil the pinching angle increases as the radius of the hollow smooth tube, but when you increase this parameter, the rink more than 0.3 m, the change in the angle of the pinching becomes insignificant. Therefore, increasing the radius of the roller over 0.3 m is not rational, since it will increase the metal content of the structure. Experimental studies of the process of tillage with a cylindrical-spiral roller allowed us to justify its optimal parameters, in which the quality criterion for soil density CCS was 0.98 (with a maximum equal to 1), which is respectively 7.1% and 14.2% more compared to ring-spur rollers and ring-shaped rollers of the seeder. The yield of barley of the Nutans-553 variety became higher after the use of an innovative cylindrical-spiral roller by 6.4 % and 9.3 %, respectively, of the yield after the impact of serial KKSh rollers and ring rollers of the seeding machine. In the course of evaluating the metal capacity of the innovative cylindrical-spiral roller and the ring-spur roller, a difference of 70% per unit width of the grip was revealed.

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