Agronomy Research **20**(4), 751–763, 2022
https://doi.org/10.15159/AR.22.055

Harrow with screw-type operating tools: optimisation of design and process parameters

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Received: August 1st, 2022; Accepted: September 8th, 2022; Published: September 9th, 2022

Abstract. A new design of the harrow with screw-type operating tools is presented in the paper. It describes the theoretical and experimental investigations carried out for the purpose of optimising the design and process parameters of the harrow with screw-type operating tools. Such optimisation will provide for improving the soil fertility, when burying chaff and other plant residues as organic fertilisers into the soil during its tillage. On the basis of the results obtained in the comprehensive experimental investigations, new regression relations have been generated. These relations provide for determining the proportion of the field surface, where the after harvesting residues have been completely buried in the soil with the harrow with screw-type operating tools. It has been established that the dominant effect on the relative amount of the field surface area S with completely worked-in plant residues is produced by the soil tillage depth h, then follows the factor of the screw-type operating device battery approach angle β. The pitch distance T of the screw-type operating device has the smallest effect. The results of the completed research prove that increasing the pitch distance T of the screw-type operating tool from 0.18 m to 0.26 m results in the decrease in the area S of the field surface with the plant residues buried in the soil by 1.4%. An increase in the approach angle β from 20° to 40° results in the increase in the field surface area S with the plant residues completely worked into the soil by 5.6%. Increasing the soil tillage depth from 0.08 m to 0.12 m results in the increase in the above-mentioned surface S by 7.1%. The simultaneous action of the factors of the tillage depth h and the approach angle β results in the percentage of the surface S rising from 72% to 82%.

Key words: diameter, disc angle, energy consumption, harrow, screw-type operating tool, soil tilling machine, tillage depth.

INTRODUCTION

One of the ponderable reserves in the improvement of the soil fertility is the utilisation of chaff and other plant residues in the quality of organic fertilisers, because the cattle-breeding industry currently does not produce a sufficient amount of manure (Aykas et al., 2005; Javadi & Hahiahmad, 2006; Damanauskas et al., 2019; Zubko et al., 2021). At the same time, mineral fertilisers are expensive and cannot provide the advantages achieved through the application of animal manure. These advantages include, first of all, the formation of organic matter and the improvement of the soil's mechanical properties manifested in the improved water absorbing and retaining power. In view of that, the field, where organic matter is regularly applied, will always be more promising in terms of the harvest, than the purely 'chemical' field. The utilisation of the residues from the harvested crop provides for the introduction into the soil of up to 60–70% of the organic matter that is effectively equivalent to classical farmyard manure. That said, the highest positive effect has been observed in rape, legume, maize and potato fields.

The soil tilling machines, in which process operations are performed by screw-type operating tools, feature such inherent qualities as simplicity in design, ease of operation, high process reliability and efficiency (Hevko et al., 2016; Boson et al., 2019). The existing methods of calculating their parameters are based on a number of recognised theoretical and experimental research works (Serrano et al., 2007, 2008; Salokhe et al., 2010; Ranjbar et al., 2013; Bulgakov et al., 2016; Kogut et al., 2016; Pylypaka et al., 2018; Zhuk & Sokht, 1018; Bulgakov et al., 2021). There is an established procedure of how to set and solve the problem of selecting the optimal parameters for screw-type operating devices in soil tilling machines with an aim to minimise their material (Hevko et al., 2016; Upadhyay & Raheman, 2018 and 2019) and energy intensity (Okyere et al., 2019; Balsari et al., 2021). However, the peculiarities associated with the performance of certain process operations impose a number of limitations.

The primary purpose of the screw-type operating tools in soil tilling machines is the high-quality performance of the process operation (soil pulverization quality, penetrability, shredding and working in of afterharvesting residues, process reliability, working width) coupled with the minimised energy and material intensity of the operating mechanism, i.e. the screw-type operating tool. The calculation of the screw-type operating tool parameters is specified by the physical and mechanical properties of the soil, the preceding crop, the harvesting technology, the technology of the soil preparation for the following crop, the initial agrotechnical requirements as well as the process schematic model of the harrows themselves.

The state of the art in the agricultural transport and process machinery stipulates looking for new ways in the improvement of the process and operation parameters of operating tools with an aim of raising the productivity and the quality of production processes and getting new operation capabilities.

The up-to-date development of transport and process machines and their operating tools has to be based on well-formed physical and mathematical models of the production processes and these models have to be operable with the use of available mathematical techniques.

The aim of this research was to improve the quality of shredding chaff and other plant residues and working them into the soil in the quality of organic fertilisers by means of optimazing the design and process parameters of the harrow with screw-type operating tools operated during the primary tillage.

MATERIALS AND METHODS

The design and process parameters of the harrow with screw-type operating tools have been optimised with an aim of raising the soil fertility with the use of chaff and other plant residues. The authors have developed a new design of the harrow, in which the operating tool is made in the form of a rod drum with helical coiling over the rods. The harrow (Fig. 1) comprises the frame 1 with the automatic hitch 2 installed in its fore end and the two batteries of screw-type operating tools 3. Each battery comprises the rod drum 4, to the outer surface of which the coils 5 of screw-type operating tools are attached, the guide 11 or 12, the clamps 13 with the fasteners 14 (the angle setting device), the battery frame 15 with the pivot pin 16. Each drum has a central axial rod, on which the framework of the operating tool is arranged. The framework comprises the two disks 6, to which the bearing assemblies 7 are attached together with the threaded axis 8 and the nuts 9, and the eight rods 10 that connect the discs 6 with each other. The rods 10 are placed symmetrically, at equal distances from each other, and attached to the circumferences of the discs 6.

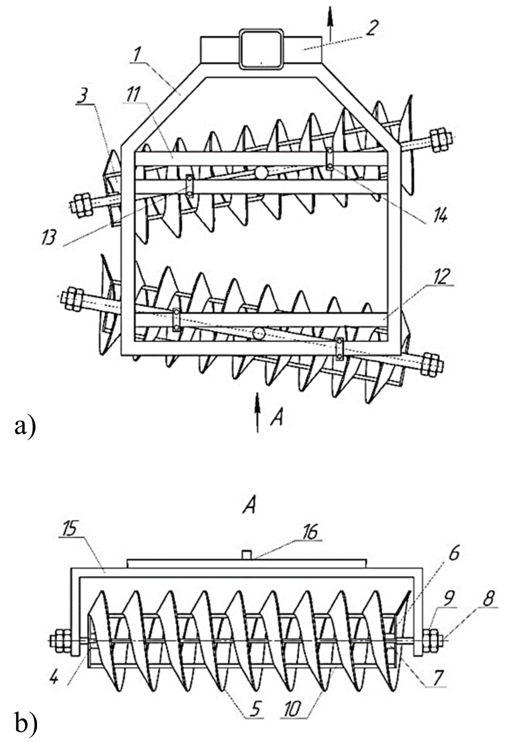

Figure 1. Structural layout of harrow with screw-type operating tools: a – top view; b – rear view along arrow *A*.

The harrow with screw-type operating tools is mounted on the wheeled aggregating tractor with the use of the automatic hitch 2. The working width and approach angle of the harrow under consideration are adjusted as follows. The screw fasteners 14 on the clamps 13 are loosened. After that, the tilling battery 3 is restrained only by the pivot pin 16 in the guides 11 (as well as 12). Both the tilling batteries 3 are shifted along the guides 11 and 12 into the required positions. For example, when operating in the 'in trail' mode, the approach (attack) angle is set within the range of $0^\circ < \beta < 40^\circ$ (depending on the soil structure). Then the fastening elements 14 of the clamps 13 are tightened and the position of the tilling batteries 3 relative to the guides 11 and 12, which defines the harrow's approach angle β and its working width, becomes fixed.

As a result of the interaction between the screw-type operating tool and the soil, a reaction force arises, which applies pressure to the working surface of the coil. One of the components of the force acts to shift the operating tool at right angle to its line of travel. In order to counterbalance this force component, it is advisable to lay out the unit with two operating tools acting in opposite phases. That is, the coils of the second operating tool have to be with the opposite winding direction and straight-line generator angle.

The described harrow with screw-type operating tools operates similarly to disk implements, which means that the profile of the tilled field features ridges and troughs. At the moment, when the blade contacts the field surface, the angles are present that are similar to the approach angle and the tilt angle of the conventional disk tools. The tilt angle can be changed by changing the straight-line surface generator angle relative to the axis of the surface. The developed new soil tilling operating tool has a simple design and a low steel intensity. As distinct from disk implements, it does not require individual bearing units for the installation of separate soil-tilling disks. The screw-type operating tools are mounted with the use of only two bearing units at the ends of each section.

The harrow with screw-type operating tools can be supplied in package with additional soil tilling batteries (for setting up combined harrowing tractor-implement units with the required working widths), which have to be with certain pre-set design parameter values. That is, the angle of tilt of the screw-type operating tool, its pitch of helix and the elevation of its coils above the rod drum have to be in accordance with the physical and mechanical properties of the soil, the depth of its tillage as well as the type and condition of the after-harvesting residues in the tilled field.

In order to optimise the design and process parameters of the new harrow with screw-type operating tools, it is necessary to set and solve an adequate optimisation problem. The problem of optimising the screw-type operating tool in a soil tillage machine is a multi-criterion problem with the following optimisation criteria: labour intensity of the auxiliary process operations F_{01}; energy consumption F_{02}; material intensity F_{03}. The sum of the cost equivalents of all the used resources can be assumed as the integrated criterion (Macmillan, 2002). That is:

$$F_0 = \varepsilon_1 \cdot F_{01} + \varepsilon_2 \cdot F_{02} + \varepsilon_3 \cdot F_{03}, \tag{1}$$

where ε_1, ε_2, ε_3 – weight coefficients of the components, which are determined essentially by the costs of the respective saved resources (labour intensity, energy consumption and material intensity).

In the process of optimising the design and process parameters of the screw-type operating tool in a soil tillage machine, the following parameters will be designated as the main optimisation parameters, i.e. the free variables: $x_1 = D$ – outer diameter of the operating tool; $x_2 = H$ – height of the helix in the screw-type operating device; $x_3 = \tan\alpha = \frac{T}{\pi D}$ – tangent of coil lead angle, defined by the pitch T of the helical spiral; $x_4 = \lambda$ – form factor of the helical surface, which takes into account the cut-outs of the helical spiral, their shapes, number and dimensions; $x_5 = \beta$ – approach angle of the operating tool; $x_6 = k_d = \frac{d}{D}$ – coefficient equal to the ratio of the internal diameter d to the external diameter D of the helical spiral; $x_7 = B$ – thickness of the helical spiral; $x_8 = L$ – length of the screw-type operating tool.

The above-listed factors have effect on the level of the criterion function F_o and its components, while their ranges of definition are determined by the constraint functions.

As an example of the process operation performance, one of the most commonly used operations can be used - the soil pulverisation and after-harvesting residue shredding. The quality of the working of the after-harvesting residues into the soil (specifically defined as the area S of the field surface with completely worked-in plant residues (%)) is designated as the optimisation criterion. It will be different for different designs and depend on the parameters x_i:

$$F_{01} = F_{01}(x_1, x_2, x_3, x_4, x_5, x_8\,) \rightarrow \min \qquad (2)$$

In general, such process operations are rather difficult to describe formally. Therefore, the optimisation of the screw-type operating tool in a soil tillage machine by this criterion is usually carried out by implementing the mathematical design of the experiment (M. Klendii & O. Klendii, 2016; E. Priporov & I. Priporov, 2021).

In that case, the criterion function is represented by a quadratic polynomial:

$$F_{01} = b_0 + \sum b_i \cdot x_i + \sum b_{il} \cdot x_i \cdot x_l + \sum b_{ii} \cdot x_i^2 \qquad (3)$$

The variation of the parameters x_i is bounded by the constraining relations $f_j = f_j(x_i)$, which are generally written in the form $f_i \leq 0$. When a mathematical design is developed, the upper and lower value limits are usually set for the factor variation, that is, $x_{\min} \leq x_i \leq x_{\max}$. *Hence:*

$$\begin{gathered} f_1 = x_{1\min} - x_1 \leq 0\,;\, f_2 = x_1 - x_{1\max} \leq 0\,;\, f_3 = x_{2\min} - x_2 \leq 0\,; \\ f_4 = x_2 - x_{2\max} \leq 0\,;\, f_5 = x_{3\min} - x_3 \leq 0\,;\, f_6 = x_3 - x_{3\max} \leq 0\,; \\ f_7 = x_{4\min} - x_4 \leq 0\,;\, f_8 = x_4 - x_{4\max} \leq 0\,;\, f_9 = x_{5\min} - x_5 \leq 0\,; \\ f_{10} = x_5 - x_{5\max} \leq 0\,;\, f_{11} = x_{6\min} - x_6 \leq 0\,;\, f_{12} = x_6 - x_{6\max} \leq 0\,. \end{gathered} \qquad (4)$$

The above limitations define the range of definition that can be represented by the following generalised constraint function in implicit form:

$$f_o = \max f_j = u_j \sum_{j=1}^{2n} f_j \prod_{k=1;k\neq j}^{2n-1} [\mu_k \cdot (f_j - f_k)] \leq 0\,, \qquad (5)$$

where u_j – undetermined Lagrange multiplier, $u_j \geq 0$; $u_k\big(f_j - f_k\big) = \frac{1+\operatorname{sgn}(f_j - f_k)}{2}$ – membership function, which is equal to $\mu_k = 1$, when $f_j > f_k$, and is equal to $\mu_k = 0$, when $f_j < f_k$.

The Lagrange function (Blinder, 2013) in accordance with each of the quality criteria is written in the form $\varphi(x,u) = F_0 + f_0$, the optimal parameters $x = \{x_1 \ldots x_i \ldots x_n\}$ can be found from the assumption $\frac{\partial\varphi(x,u)}{\partial x_i} = 0$. Consequently, the optimal parameters x_i^{opt} are determined by means of solving the linear equation system that comprises n equations, $i = (1 \ldots n)$.

$$\frac{\partial\varphi(x,u)}{\partial x_i} = b_i + 2 \cdot b_{ii} + \sum_{l,l\neq i}^{n} b_{il} \cdot x_l + u_j \sum_{j=1}^{2n} \left(\frac{\partial f_j}{\partial x_i}\right) \prod_{k=1;k\neq j}^{2n-1} [\mu_k \cdot (f_j - f_k)] \qquad (6)$$

The condition $\frac{\partial f_j}{\partial x_i} = \text{const}$ is applied to the linear constraint functions f_j. Accordingly, for the constraint function $f_1 = x_{1min} - x_{x1} \leq 0$ the condition $\frac{\partial f_j}{\partial x_i} = -1$ is applied, for $f_2 = x_1 - x_{1\max} \leq 0$ – $\frac{\partial f_j}{\partial x_i} = 1$. The component $\vartheta = \prod_{k=1;k\neq j}^{2n-1} [\mu_k \cdot (f_j - f_k)$, which is equal to 0 or 1, automatically selects the constraint function, at the limit of which the parameters can have optimal values. The use of (5) in the optimisation problem substantially simplifies the algorithms of its solving, which provides for the computerisation of the computation process.

In case the soil tillage process is optimised under the constraints (4), the system (6) appears as follows:

$$\left.\begin{aligned}
\frac{\partial\varphi(x,u)}{\partial x_1} &= b_1 + 2 \cdot b_{11} + \sum_{l,l\neq 1}^{n} b_{1l} \cdot x_l - u_{1,} + u_2; \\
\frac{\partial\varphi(x,u)}{\partial x_2} &= b_2 + 2 \cdot b_{22} + \sum_{l,l\neq 2}^{n} b_{2l} \cdot x_l - u_3 + u_4; \\
\frac{\partial\varphi(x,u)}{\partial x_3} &= b_3 + 2 \cdot b_{33} + \sum_{l,l\neq 3}^{n} b_{3l} \cdot x_l - u_5 + u_6; \\
\frac{\partial\varphi(x,u)}{\partial x_4} &= b_4 + 2 \cdot b_{44} + \sum_{l,l\neq 4}^{n} b_{4l} \cdot x_l - u_7 + u_8; \\
\frac{\partial\varphi(x,u)}{\partial x_5} &= b_5 + 2 \cdot b_{55} + \sum_{l,l\neq 5}^{n} b_{5l} \cdot x_l - u_{9,} + u_{10}; \\
\frac{\partial\varphi(x,u)}{\partial x_6} &= b_6 + 2 \cdot b_{66} + \sum_{l,l\neq 4}^{n} b_{6l} \cdot x_l - u_{11} + u_{12}.
\end{aligned}\right\} \qquad (7)$$

When the optimal values of the tillage parameters are selected with the use of the developed mathematical design of experiment, the optimal parameters take on either values within the range of definition or the limiting values of the range. In case of the former option, $u_j = 0$ and the Lagrange function corresponds to the criterion function (2), therefore, the system of equations is significantly simplified.

In case $\frac{\partial F_0}{\partial x_i} > 0$, the parameter x_i takes on the minimum value $x_i = x_{\min}$ and one of the undetermined multipliers becomes $u_{2i} = 0$. On the other hand, when $\frac{\partial F_0}{\partial x_i} < 0$, the parameter takes on the value $x_i = x_{\max}$, and the other undetermined multiplier becomes $u_{2i-1} = 0$.

The results of solving the above problem provide the basis for determining the operating device parameters: the approach angle of the operating tool β; the tangent of coil lead angle $\tan\alpha$; the soil tillage depth h (height of the spiral of the screw-type operating tool) and the shape of the helical surface. The earlier research has proved that the use of the rational parameter value for the operating tool approach angle β in the process of working in the plant residues results in achieving the tilled field surface area

S with the plant residues completely worked into the soil that approaches a level of 90–100%. For the purpose of conducting experimental research, a harrow with screw-type operating tools (Fig. 1) has been engineered with the following initial parameters: length of the spiral $L = 1.3$ m; external diameter of the helical surface $D = 0.56$ m, its internal diameter $d = 0.32$ m; height of the spiral of the screw-type operating tool $H = 0.12$ m; pitch distance of the helical spiral $T = 0.25$ m. When the concentration of the key component was equal to 80%, the rational value of the operating tool approach angle was $\beta = 40°$.

When the process is optimised in terms of the criterion of the energy consumption during soil tillage, it is reasonable to designate the tractive resistance of the screw-type operating tool as the criterion function, which can be represented by the following relation (Nadykto et al., 2015):

$$P = k \cdot A \cdot n \cdot \sin\beta[1 + \tan(\gamma + \varphi)], \tag{8}$$

where k – specific resistance of the soil, $k = 20–130$ kN m^{-2}; A – area of contact between the front surface of the coil of the screw-type operating tool and the soil, m^2; β – approach (attack) angle of the screw-type operating tool; n – number of the screw-type operating tool coils simultaneously penetrating the soil; γ – angle between the front working surface of the screw-type operating tool coil and the furrow wall; φ – angle of repose of the soil on the working surface of the screw-type operating tool coil.

The analysis of the expression (8) has proved that the most efficient way of reducing the energy spent for the movement of the harrow, simultaneously ensuring the optimal operating speed conditions, is to use antifriction materials in the design of screw-type operating tools, that is, to reduce the coefficient of friction between the soil and the working surface of the screw-type operating tool coil. That said, the approach angle of the screw-type operating tool has to be maximal to ensure the sufficient quality of the performed soil tillage.

In terms of the material intensity of the operating tool, the criterion is the ratio of the unit length harrow’s mass to the required productivity Q. The material intensity criterion is applied, when it is a decisive factor. In that case, the problem of minimising the material intensity (cost) of the harrow is set by the criterion:

$$F_{03} = \alpha_1 V_1 + \alpha_2 V_2 + \alpha_3 V_3 \to \min, \tag{9}$$

where V_1, V_2, V_3 – volumes of the harrow frame, the helical spiral and the central rod axis, respectively; α_1, α_2, α_3 – respective densities ρ_i (or production costs) of the materials, from which the helical spiral of the harrow is made.

The following process, design and operation constraints are applied, when determining the optimal parameters of the screw-type operating tool in a soil tillage machine and the soil tillage work process:

1. The process constraint of shaping the spiral from a flat work piece:

$$f_1 = -k_d + \frac{\sqrt{\pi^2 + 1 - c^2}}{\pi \cdot c} \leq 0, \tag{10}$$

where $f_1 = -k_d + \frac{\sqrt{\pi^2+1-c^2}}{\pi \cdot c} \leq 0,$ – permissible coefficient of metal elongation irregularity determined by the coefficient of elongation $c = (1 + 2 \cdot B)^2$.

2. The process constraint of ensuring the stability of the flat bar in the process of manufacturing the spiral:

$$f_2 = D \cdot (1 - k_d) - \frac{2 \cdot H}{B} \leq 0, \tag{11}$$

where B – allowable specific thickness of the metal work piece used for manufacturing the helical spiral, obtained by rolling – B = 0.02–0.03 mm; obtained by coiling – B = 0.05–0.70 mm.

3. The constraint of the minimal spiral thickness that is sufficient to resist the loss of the spatial stability by the coil:

$$f_3 = -B + B_{\min} \leq 0 \tag{12}$$

where $B_{\min}$ – minimal acceptable thickness of the helical spiral blank determined experimentally.

4. The constraint of ensuring the stability of the helical spiral in operation:

$$f_4 = \frac{K_{CT} \cdot B \cdot H^3 \cdot E}{\sqrt{1 + K_T}} - T \leq 0 \tag{13}$$

where K_{CT} – experimental coefficient; E – Young's modulus; k_T – helix pitch distance coefficient.

The following parameters are taken as independent ones in the optimisation of the operating tools: $x = (x_i) = (D, \lambda, \tan\alpha, \beta, L, k_d\,, H)$. At this stage, the following function is taken as the criterion function: $F_0 = F_{03}$.

Taking into account the above description of the criterion function, it can be written in the following form:

$$F_{03} = \pi x_1 \left[\alpha_1 S_K \left(1 + x_2 + \frac{S_K}{x_1} \right) + \alpha_2 x_7 \left(1 - x_6 \right) \sqrt{1 + \frac{1}{x_3}} + \pi \alpha_3 S_d x_1 \left(x_6 - \frac{S_d}{x_1} \right) \right], \tag{14}$$

where S_k – thickness of the harrow frame; S_d – diameter of the central rod shaft.

It is necessary to determine the partial derivatives of the function. They appear as follows:

$$\begin{aligned}
&\frac{dF_{03}}{dx_1} = \alpha_1 \pi (S_k + x_2) + \alpha_3 \pi S_d x_6;\\
&\frac{dF_{03}}{dx_2} = \alpha_1 \pi S_k x_1;\\
&\frac{dF_{03}}{dx_3} = \frac{\alpha_1 x_7 (1 - x_6) + \alpha_3 \pi S_d x_6}{x_3^2 \sqrt{1 + \frac{1}{x_3}}};\\
&\frac{dF_{03}}{dx_6} = \alpha_3 \pi S_d x_1;\\
&\frac{dF_{03}}{dx_3} = \alpha_2 (1 - x_6) \sqrt{1 + \frac{1}{x_3}}.
\end{aligned} \tag{15}$$

The analysis of the partial derivatives of the function F_{03} has proved that it reaches its minimums at the extreme values of x_i, in particular, at the minimum values: $x_i = D$; $x_2 = \frac{2z}{D}$; $x_6 = k_d = \frac{d}{D}$; $x_7 = H$ and at the maximum value: $x_3 = \tan\alpha = \frac{T}{\pi D}$.

Accordingly, the possible solutions that will meet the Kuhn-Tucker conditions can be found from the systems of equations set up on the basis of the constraint functions.

The obtained relations provide for calculating with high accuracy the optimal design and process parameters of the screw-type operating tool. Such parameters will ensure the required quality of the soil tillage at a high efficiency of the process.

The experimental research into the efficiency of the process of working the plant residues into the soil (which implies determining the percentage of the field plot surface area *S* with the plant residues completely worked in, %) was carried out in field conditions during the cultivation of a wheat stubble field. The soil had the following properties: type of soil - grey podzolized, crushing strength value (hardness) - 87.4 kN m^{-2}, absolute moisture content - 18%, soil density - 1.6 kg m^{-3}. The harrow with screw-type operating tools during the field experiment investigations is shown in Fig. 2.

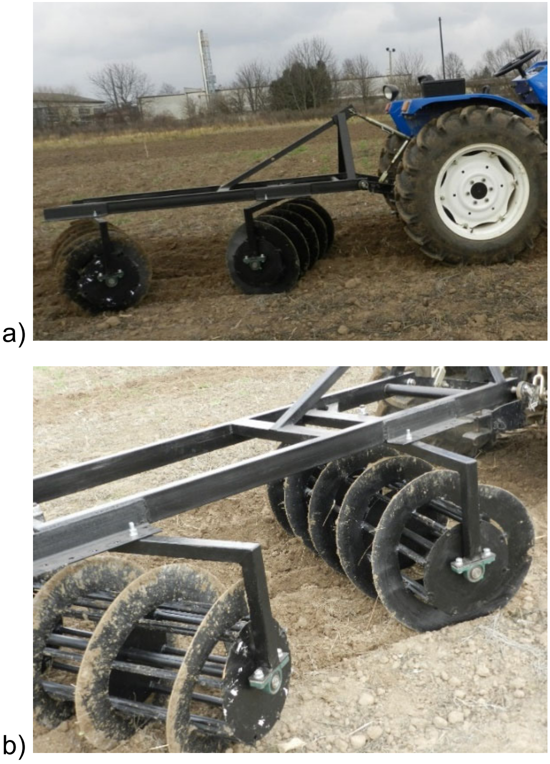

Figure 2. Harrow with screw-type operating tools: a) – general view; b) – side view.

In the selected plot, the soil was tilled with the use of the harrow with screw-type operating devices. After the tillage of a certain area (approximately 100 m^2) was complete, the quality of the work was investigated, then the operating tools in the harrow were changed (operating devices of different designs and sizes had been prepared for the experiments) and their positions with respect to the line of travel were readjusted.

The programme of experimental research included the experiments aimed at finding the relations between the proportion of the field plot surface area *S* with the plant residues completely worked into the soil and: 1) the positioning angle of the screw-type operating tool battery with respect to the travel line (approach angle β); 2) the screw-type operating tool pitch distance *T* and 3) the soil tillage depth *h*. The peak (maximum) values obtained during the experimental investigations were used to analyse the value of the investigated parameter.

The efficiency of the plant residue working in process was estimated using the method of spectral analysis. The information for the analysis was obtained from the series of photographic images shot from a height of 10 m (ensuring a longitudinal photograph overlap of at least 60% in accordance with the photogrammetry requirements) with the camera of a DJI Phantom 4 quadrocopter. The resulting images were processed in the computer programme Agisoft Photoscan and on their basis the cartographic materials were generated. For determining the percentage of the field surface area with the plant residues completely worked in, the geographic information system (GIS) QGis 3 was used. Within the system, controlled classification of the soil was carried out using the training sample method.

For each of the factors, the experiments were done with at least 3 replicates. Then the mean value was determined for each of the results and that value would be used for the further statistical analysis of the experimental results.

With an aim of determining how various design and process parameters of the screw-type operating tools in the harrow (i.e. the independent factors x_i) influence the proportion of the field plot surface area S with the plant residues completely worked into the soil, full factorial experiments were carried out. Basing on the results of the experiments, the relations between the above-mentioned indicator and the three main variable factors: the approach angle β (deg) of the operating tool, the pitch distance T (m) of the screw-type operating device and the soil tillage depth h (m), i.e. $S = f(\beta, T, h)$, were established. The respective data are presented in Table 1.

Table 1. Description of factors and their levels in experimental investigations for determining field surface area with plant residues completely worked into soil

Factor	Designation		Variation interval	Levels of variation, actual/coded		
	Coded	Actual				
Operating tool approach angle β, deg	X_1	x_1	10	20/-1	30/0	40/+1
Screw-type operating tool pitch distance T, m	X_2	x_2	0.04	0.18/-1	0.22/0	0.26/+1
Tillage depth h, m	X_3	x_3	0.02	0.08/-1	0.10/0	0.12/+1

After coding the factors, the design matrix was generated for the appropriate multifactorial experiment – a 3^3 full factorial experiment with the number of experiments $N = 3^3$.

The general regression equation for the percentage of the field surface area S with the plant residues completely worked into the soil as a function of the variable operating tool approach angle β, the screw-type operating tool pitch distance T and the soil tillage depth h, i.e. $S = f(\beta, T, h)$, appeared as follows:

$$S = 81.205 - 33.33T - 245.32h + 2.84\beta h + 1{,}639.61h^2. \qquad (16)$$

The obtained regression equation (16) was used for determining the percentage of the field area S with the plant residues completely worked into the soil in relation to the following three main varying factors: operating tool approach angle β, screw-type operating tool pitch distance T and soil tillage depth h. The ranges of variation of the input factors were as follows: $20 \le \beta \le 40$ deg; $0.18 \le T \le 0.26$ m; $0.08 \le h \le 0.12$ m.

RESULTS AND DISCUSSION

The Statistica-6.0 software was used to plot the graphic relations of the transitional general regression models. They were plotted in the form of quadratic response surfaces for the percentage of the field surface area S with the plant residues completely worked in as a function of two variable factors $x_{i(1,2)}$ at a constant invariable level of the respective third factor $x_{i(3)}$ = const. The resulting graphic relations of the area S with buried plant residues, obtained with the use of the Statistica-6.0 software, are presented in Fig. 3.

The analysis of the obtained regression equation has proved that the factors x_3, x_1, (h, β) and the combinations of these factors have the greatest effect on the changes in the percentage of the field surface area with the plant residues completely worked in. Increasing the value of the factor x_3(h) results in an increase of 7.4% in the percentage of the field surface area with the plant residues completely worked in. Overall, in order to increase the percentage of the field surface area with the plant residues completely worked in, it is necessary to increase the depth of tillage and the approach angle β and to decrease the pitch distance of the screw-type operating tool.

The analysis of the response surfaces shown in Fig. 3 makes it obvious that an increase in the tillage depth results in an increase in the proportion of the field surface area, where the plant residues have been worked in, the maximum percentage value being at 84%. The minimum proportion of the field surface area with the plant residues completely worked in is equal to 67% and it occurs at the minimum value of the approach angle β and the maximum value of the screw-type operating tool pitch distance T.

It has been established that increasing the screw-type operating tool pitch distance T from 0.18 m to 0.26 m results in the proportion of the field surface area S, where the plant residues have been worked in, decreasing by 1.4%. At the same time, increasing the approach angle β from 20 deg to 40 deg results in the percentage of the field surface area S with the plant residues completely worked into the soil increasing by 5.6%. An increase in the soil tillage depth h from 0.08 m to 0.12 m results in the field surface area S with the plant residues completely worked into the soil increasing by 7.1%. Simultaneous increases in the tillage depth h and approach angle β result in the field surface area S with the plant residues completely worked into the soil increasing from 72% to 82%.

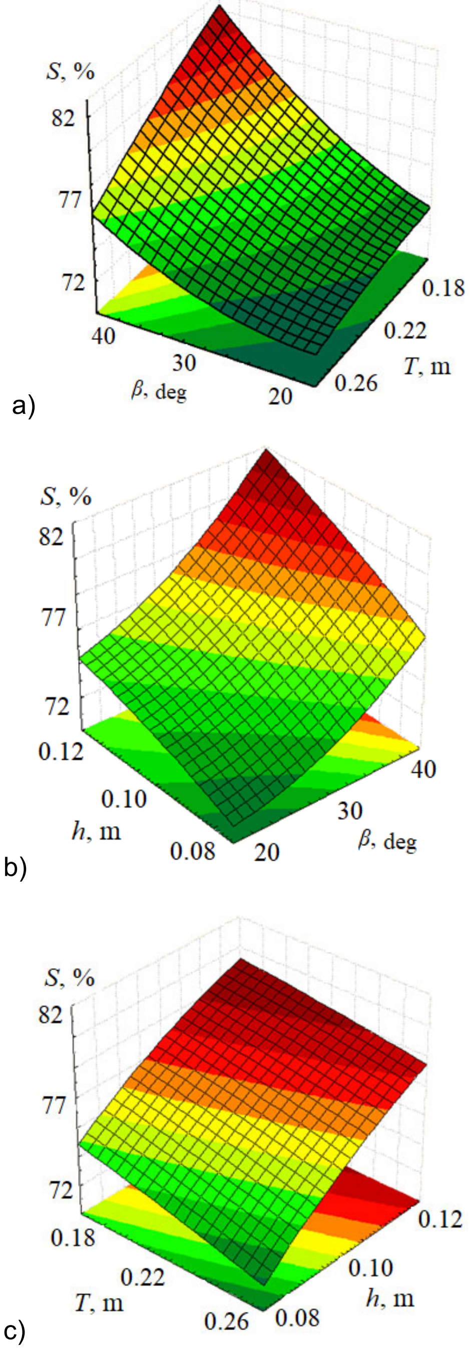

Figure 3. Response surfaces for variation of field plot surface area S with completely buried plant residues as a result of variation of soil tillage factors:
a – $S = f(\beta, T)$; b – $S = f(h, \beta)$; c – $S = f(T, h)$.

CONCLUSIONS

A new design of the harrow with screw-type operating tools has been developed and a pilot unit has been manufactured. The design and process parameters of the harrow with screw-type operating tools have been optimised with an aim of raising the soil fertility by way of working in chaff and other plant residues as organic fertilisers during soil tillage.

A set of experimental investigations has been carried out. On the basis of their results, the regression relations have been derived that provide for determining the percentage of the field plot surface area *S*, where the plant residues are completely worked in by the harrow with screw-type operating tools. It has been established that the soil tillage depth *h* has the dominant effect on the percentage of the field plot surface area *S* with the plant residues completely worked in, then follows the approach angle *β* of the screw-type operating tool battery. The pitch distance *T* of the screw-type operating tool has the smallest effect. The response surfaces that represent the relations between the percentage of the field plot surface area *S*, where the plant residues are completely worked in by the harrow with screw-type operating tools, and the main factors have been plotted. By analysing these surfaces, it has been established that increasing the soil tillage depth *h* results in the percentage of the field plot surface area *S* with the plant residues completely worked in rising, its highest value being equal to 84%. The minimum value of the percentage of the field plot surface area *S* with the plant residues completely worked in is equal to 67% and it occurs at the minimum approach angle *β* and the maximum pitch distance *T* of the screw-type operating tool.

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