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Investigation of the separation of combed heap of winter wheat

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Abstract. The article deals with the problem of separation of combed heap of winter wheat with an experimental working unit consisting of a segregator and a sieve. In order to expand the range of information on the qualitative side of the functioning of the working unit, it is suggested to introduce an additional assessment parameter – the impurity separation efficiency coefficient. Experimental studies of the technological process of the working unit were carried out using the mathematical theory of experimental design, where the response function was represented by the functional dependence of the change in the impurity separation efficiency coefficient on the specific feed of the combed heap, the oscillation frequency of the working unit and the diameter of the sieve openings. To conduct the experimental studies, the Box-Behnken design was selected. Verification of the significance of the obtained coefficients according to Student's t-test showed that all the coefficients were significant. The adequacy of the model was assessed according to Fisher's test. As a result of the calculations, it was established that the model was adequate and could be used for further research.

1. Introduction

Nowadays, the main method of harvesting crops is the traditional combine harvester method. Nonetheless, it has significant drawbacks, including high transportation costs, the problem of harvesting lodged grain, the inability to harvest wet grain mass etc. [1]. At the same time, the main



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disadvantage of this technology is the limited specific capacity of the threshing and separating device, which can be increased by either modernizing the threshing and separating device [2] or by improving the separation process in grain cleaning system of the combine harvester [3], as well as by improving the grain separation in the straw walker of the combine harvester [4]. However, this does not solve the problem in general. All the downsides of the traditional technology can be fundamentally eliminated with the use of technology of combing plants on the stalk, the justification for which is given in the paper [5], and its analysis is provided in the article [6]. Implementation of the method of combing plants on the stalk is possible in both the combine harvester method [7-8] and the stationary method [9]. The method of combing plants on the stalk is the most effective while using the stationary mode [10]. This technology involves collecting the combed heap in the field and its refinement at a stationary site [9]. However, the quality of this operation is constrained by the shortage of technical equipment. The problem lies within the fact that the fractional composition of the combed heap, according to the analysis given in the paper [11], differs significantly from the grain heap obtained from combine harvesters. Commercially available heap cleaners are not effective for its separation [12-14], as well as experimental vibratory [15] and gravitational separators [16] and low-speed cylindrical sieves [17]. Such a complex fractional composition of the heap can be separated with a flat-mesh separating unit, the results of its study were considered in the paper [11]. The present article provides the analysis of the technological process of the working unit for the separation of the combed wheat heap using the mathematical theory of experimental design, where the specific feed of the raw material to the working unit, the oscillation frequency and the diameter of the sieve openings were taken into account as factors. A change in the separation coefficient was adopted as the response function. However, using only the quality indicator of the technological process during the separation of such complex material is not enough.

It is suggested to introduce another indicator to assess the functioning of the separating working unit — the impurity separation efficiency coefficient, which is obtained by the formula:

$$\nu = 1 - \frac{\xi_2}{\xi_1}, \quad (1)$$

where ν is the impurity separation efficiency coefficient;

ξ_1 is the impurity content in the raw material, %;

ξ_2 is the impurity content in the purified material, %.

The impurity separation efficiency coefficient contains information about the qualitative side of the separation process, i.e. it characterizes the work of the experimental working unit from the perspective of isolating large impurities, mainly straw and torn spikelets.

2. Material and methods

The program of the research included the following steps:

- carrying out a full factorial experiment;
- calculation of regression coefficients and verification of their significance according to Student's t-test;
- assessment of the adequacy of the obtained regression equation according to Fisher's test;
- study of the regression equation by means of mathematical analysis;
- geometric interpretation of the results by methods of constructing response surfaces.

The first stage in the implementation of the proposed program was carrying out the experimental studies. The experiments were performed on an experimental laboratory facility, the general view of which is shown in Figure 1, and its technological scheme, description of the design and working process are given in the paper [11].

To conduct the experimental studies, a noncomposite, rotatable three-level Box-Behnken design was selected (Figure 1), while the specific feed of the combed heap to the working unit, $\text{kg/s} \cdot \text{m}^2$, its oscillation frequency, s^{-1} , and the diameter of the sieve openings, mm, have been taken into account

as factors, similar to those in the paper [11]. The required level of the specific feed was provided using a gravity conveyor, the oscillation frequency was controlled by an autotransformer, and to vary the size of the sieve openings, three variable sieves with different opening diameters were made (Figure 2), while the design of working unit (Figure 3) made it easy to change them.



Figure 1. General view of the experimental laboratory facility

As noted earlier, the function of a change in the impurity separation efficiency coefficient was adopted as the response function.

Levels of variation of the factors are provided in the paper [11].



Figure 2. General view of variable sieves with different opening diameters: d=15 mm; b. d=25 mm; c. d=35 mm

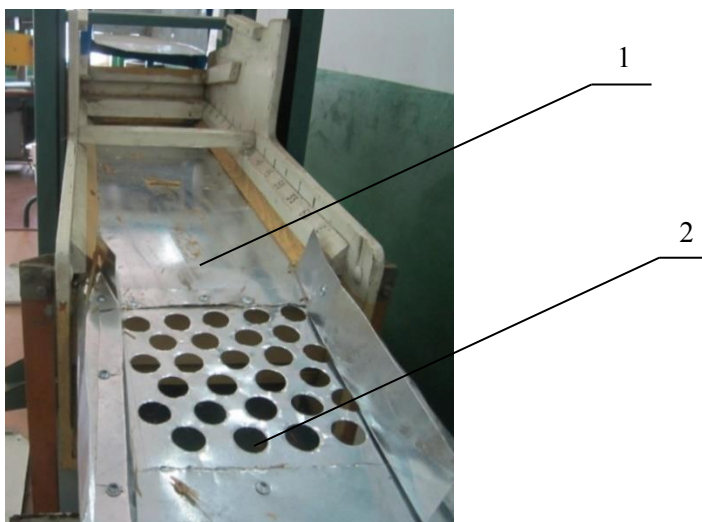


Figure 3. General view of the separating working unit: 1. segregator; 2. sieve

The experiments were carried out according to the compiled matrix in triplicate, while the regression coefficients were calculated using the known formulas given in the paper [18].

The general form of the regression equation can be represented as follows:

$$y_2 = c_0 + c_1x_1 + c_2x_2 + c_3x_3 + c_{12}x_1x_2 + c_{13}x_1x_3 + c_{23}x_2x_3 + c_{11}x_1^2 + c_{22}x_2^2 + c_{33}x_3^2, \quad (2)$$

where y_2 is the response function characterizing the change in the impurity separation efficiency coefficient;

x_1 is the specific feed of the combed heap to the working unit;

x_2 is the oscillation frequency of the working unit;

x_3 is the diameter of the sieve openings;

$c_0, c_1, c_2, c_3 \dots$ are regression coefficients.

3. Results and discussion

Carrying out a full factorial experiment made it possible to obtain primary information about the process of the change in the impurity separation efficiency coefficient depending on the value of the factors. According to the known method described in the paper [19], the regression coefficients were calculated, as well as their confidence intervals, the adequacy of the obtained mathematical model was assessed, the results of the calculations are provided in Table 1.

Table 1. Parameters of the mathematical model

Name of model parameters	Calculated values
Regression coefficients	$c_0 = 0.6$ $c_1 = -0.105$ $c_2 = -0.104$ $c_3 = 0.054$ $c_{12} = 0.015$ $c_{13} = 0.03$ $c_{23} = 0.01$ $c_{11} = -0.046$ $c_{22} = 0.049$ $c_{33} = -0.009$
Confidence intervals of regression coefficients	$\Delta c_0 = \pm 0.00086$ $\Delta c_i = \pm 0.000034$ $\Delta c_{ij} = \pm 0.000067$ $\Delta c_{ii} = \pm 0.000265$
Dispersion of reproducibility	$S^2\{y\} = 0.0000625$
Dispersion of adequacy	$S^2 = 0.000466$
Calculated value of Fisher's test	$F_1 = 7.456$
Tabulated value of Fisher's test	$F_2 = 19.3$

As can be seen from Table 1, the numerical values of the regression coefficients turned out to be greater than their confidence intervals, which leads to a conclusion that all the regression coefficients are significant. Thus, taking into account equation (2) and the calculated coefficients, we obtain the regression equation.

$$y_2 = 0.6 - 0.105x_1 - 0.104x_2 - 0.054x_3 + 0.015x_1x_2 + 0.03x_1x_3 + 0.01x_2x_3 - 0.046x_1^2 + 0.049x_2^2 - 0.009x_3^2. \quad (3)$$

To assess the adequacy of the obtained mathematical model, Fisher's test was used. As can be seen from table 1, $F_2 > F_1$, on the basis of this inequality we can conclude that the resulting model is adequate.

Let us examine the obtained regression equation by methods of mathematical analysis for the maximum and minimum values, according to the procedure described in [20]. Let us take the partial derivatives of the function y_2 with respect to the factors x_1 , x_2 and x_3 , resulting in:

$$\begin{aligned}\frac{\partial y_2}{\partial x_1} &= -0.105 + 0.015x_2 + 0.03x_3 - 0.092x_1, \\ \frac{\partial y_2}{\partial x_2} &= -0.104 + 0.015x_1 + 0.01x_3 + 0.098x_2, \\ \frac{\partial y_2}{\partial x_3} &= -0.054 + 0.03x_1 + 0.01x_2 - 0.018x_3.\end{aligned}\quad (4)$$

Let us set each equation of system (4) to zero and solve the resulting system of equations with respect to the unknowns x_1 , x_2 and x_3 .

As a result of the solution of the system of equations, we obtain $x_1 = -2.98$, $x_2 = 2.205$ and $x_3 = -6.742$. As can be seen from the results obtained, the numerical values of the factors lie outside the area of factorial space. Now let us examine in stages the response function y_2 at the boundary of the closed space. During the first stage, let us study the response function provided that $x_1 = c_1 = \text{const}$, at the second stage we will carry out research provided that $x_2 = c_2 = \text{const}$, and at the third stage $x_3 = c_3 = \text{const}$.

Let us consider alternately the examination in all the three cases.

1. For $x_1 = c_1 = \text{const}$ equation (3) takes the following form:

$$y_2 = 0.6 - 0.105c_1 - 0.104x_2 - 0.054x_3 + 0.015c_1x_2 + 0.03c_1x_3 + 0.01x_2x_3 - 0.046c_1^2 + 0.049x_2^2 - 0.009x_3^2.\quad (5)$$

Let us take the partial derivatives of the function y_2 with respect to the factors x_2 and x_3 .

$$\begin{cases} \frac{\partial y_2}{\partial x_2} = -0.104 + 0.015x_1 + 0.01x_3 + 0.098x_2, \\ \frac{\partial y_2}{\partial x_3} = -0.054 + 0.03x_1 + 0.01x_2 - 0.018x_3. \end{cases}\quad (6)$$

Let us set to zero each equation of system (6)

$$\begin{cases} -0.104 + 0.015x_1 + 0.01x_3 - 0.098x_2 = 0, \\ -0.054 + 0.03x_1 + 0.01x_2 - 0.018x_3 = 0. \end{cases}\quad (7)$$

Let us solve the linear system of equations (7) with respect to the unknowns x_2 and x_3 , and as a result we obtain the following equations:

$$\begin{cases} x_2 = \frac{241.2 - 57c_1}{186.4}, \\ x_3 = 1.497c_1 - 2.2811. \end{cases}\quad (8)$$

As can be seen from equation (8), the factors obtained as a result of solving the system of linear equations (7) x_2 and x_3 , depend on the value of c_1 . According to the assumptions incorporated in the model, c_1 may have a value of: -1; -0.5; 0; 0.5; 1.

Let us carry out a computer experiment, the purpose of which is to determine the values of the response function y_2 in each of the sections and at the nodal points. After calculating the values of y_2 at 25 points of the factorial space it turned out that the response function takes the maximum value of 0.912 at $x_1 = -1, x_2 = -1$ and $x_3 = -1$.

2. We adopt that $x_2 = c_2 = const$ and put c_2 into equation (4) instead of x_2 , as a result we obtain the following equation:

$$y_2 = 0.6 - 0.105x_1 - 0.104c_2 - 0.054x_3 + 0.015x_1c_2 + 0.03x_1x_3 + 0.01c_2x_3 - 0.046x_1^2 + 0.049c_2^2 - 0.009x_3^2.$$

Let's take partial derivatives of the response function y_2 by factors x_1 and x_3 , i.e.

$$\begin{cases} \frac{\partial y_2}{\partial x_1} = -0.105 + 0.015c_2 + 0.03x_3 - 0.092x_1, \\ \frac{\partial y_2}{\partial x_3} = -0.054 + 0.03x_1 + 0.01c_2 - 0.018x_3. \end{cases} \quad (9)$$

We set each equation of system (9) to zero and obtain a system of linear equations:

$$\begin{cases} -0.105 + 0.015c_2 + 0.03x_3 - 0.092x_1 = 0, \\ -0.054 + 0.03x_1 + 0.01c_2 - 0.018x_3 = 0. \end{cases} \quad (10)$$

After solving the system of equations (10) with respect to the unknowns x_1 and x_3 , we obtain:

$$\begin{cases} x_1 = \frac{117 - 19c_2}{85.2}, \\ x_3 = \frac{3.3c_2 - 12.8}{18}. \end{cases} \quad (11)$$

We adopt that c_2 may have the following values: -1; -0.5; 0; 0.5; 1.

Let us carry out another computer experiment, similar to the one conducted earlier.

The results of the calculation of values of y_2 at 17 points of the factorial space showed that the response function takes its maximum value of 0.81 at the following values of the factors: $x_1 = -1, x_2 = -0.5$ and $x_3 = -1$.

3. Let us adopt that $x_3 = c_3 = const$ and put x_3 into equation (3).

$$y_2 = 0.6 - 0.105x_1 - 0.104x_2 - 0.054c_3 + 0.015x_1x_2 + 0.03x_1c_3 + 0.01x_2c_3 - 0.046x_1^2 + 0.049x_2^2 - 0.009c_3^2. \quad (12)$$

Then we take the partial derivatives of the response function for variables $x_1 = -1$ and $x_2 = -1$.

$$\begin{cases} \frac{\partial y_2}{\partial x_1} = -0.105 + 0.015x_2 + 0.03c_3 - 0.092x_1, \\ \frac{\partial y_2}{\partial x_2} = -0.104 + 0.015x_1 + 0.01c_3 + 0.098x_2. \end{cases} \quad (13)$$

Let us set each equation of system (13) to zero.

$$\begin{cases} -0.105 + 0.015x_2 + 0.03c_3 - 0.092x_1 = 0, \\ -0.104 + 0.015x_1 + 0.01c_3 + 0.098x_2 = 0. \end{cases} \quad (14)$$

After solving the system of equations with respect to the unknowns $x_1 = -1$ and $x_2 = -1$ we obtain the following equations:

$$\begin{cases} x_1 = \frac{-14.17 + 4.529c_3}{15}, \\ x_2 = \frac{1114.3 - 137c_3}{924.1}. \end{cases} \quad (15)$$

Let us carry out the final computer experiment to calculate the response function y_2 , provided that c_3 can have the following values: -1; -0.5; 0; 0.5; 1. The experiment showed that the response function y_2 takes its maximum value of 0.871 at the values of the factors $x_1 = -1, x_2 = -1$ and $x_3 = -0.5$.

Analyzing the results obtained during three computer experiments, it should be noted that the response function takes its maximum value of 0.912 at the following values of the factors: $x_1 = -1, x_2 = -1$ and $x_3 = -1$.

The geometric interpretation of the obtained results is represented by the response surfaces. The method of their construction is given in the paper [11].

Let us consider the response surface x_1x_2 of the separation efficiency coefficient, provided that factor x_3 is fixed at $x_3 = -1$ (Figure 4). The maximum value of 0.912 of the impurities separation efficiency coefficient is observed at $x_1 = -1$ and $x_2 = -1$. With an increase of the specific feed and the oscillation frequency of the working unit, the impurities separation efficiency coefficient decreases and reaches its minimum value of 0.414 at the specific flow of the combed heap equal to $3.3 \text{ kg/s} \cdot \text{m}^2$ and the oscillation frequency of 55 s^{-1} .

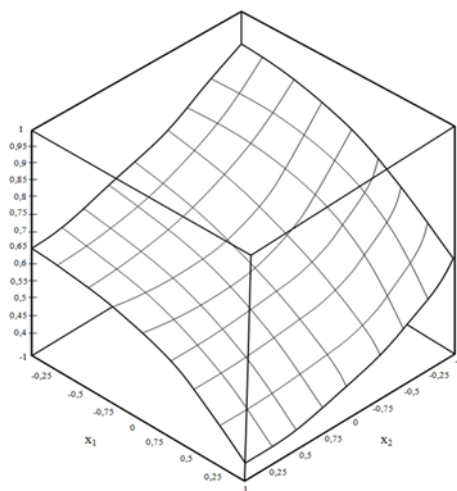


Figure 4. The response surface x_1x_2 of the separation efficiency coefficient, factor x_3 is fixed at $x_3 = -1$

The response surface x_1x_3 reaches its maximum value of the impurities separation efficiency coefficient of 0.912 at $x_1 = -1$ and $x_3 = -1$, which corresponds to the specific feed of the combed heap equal to $2.1 \text{ kg/s} \cdot \text{m}^2$ and the sieve openings diameter equal to 15 mm at the oscillation frequency of the working unit of 45 s^{-1} .

With the increase of the specific feed and the diameter of the sieve openings, the impurities separation efficiency coefficient decreases. Its minimum value of 0.53 is observed at the specific feed of the combed heap of $3.3 \text{ kg/s} \cdot \text{m}^2$ and the sieve openings diameter equal to 0.35 mm, provided that the oscillation frequency of the working unit equals to 55 s^{-1} .

Finally, let us consider the response surface x_2x_3 of the impurities separation coefficient. The highest quality of functioning of the working unit is observed at $x_2 = -1$ and $x_3 = -1$, whereas the impurities separation coefficient equals to 0.912 (Figure 5).

Thus, the response surfaces (Figures 4-6) clearly demonstrate that the maximum value of the impurities separation efficiency coefficient is observed at the specific feed of the combed heap to the operating body of $2.1 \text{ kg/s} \cdot \text{m}^2$, the oscillation frequency of the working unit equal to 45 s^{-1} and the diameter of the sieve openings equal to 15 mm.

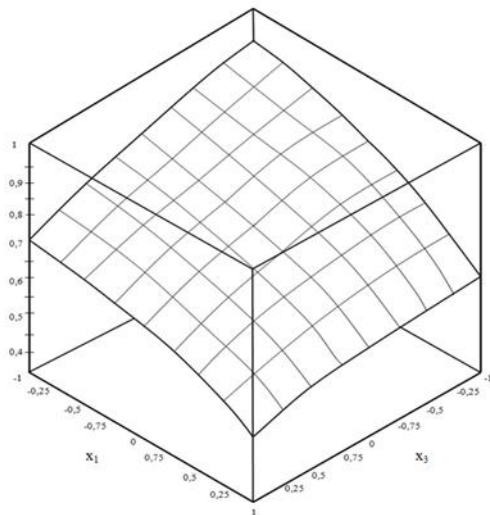


Figure 5. The response surface x_1x_3 of the separation efficiency coefficient, factor x_2 is fixed at $x_2 = -1$

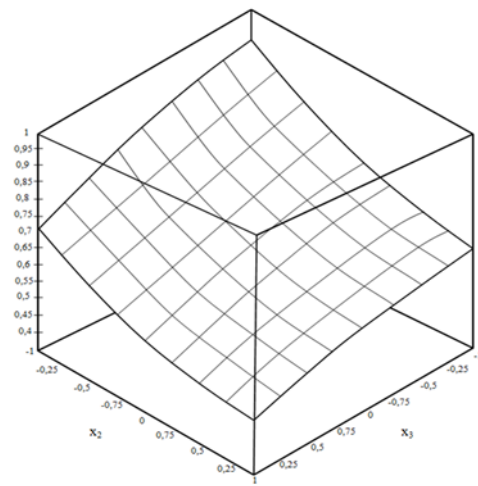


Figure 6. The response surface x_2x_3 of the separation efficiency coefficient, factor x_1 is fixed at $x_1 = -1$

4. Conclusions

1. It is suggested to introduce an additional assessment parameter of the quality of functioning of the separating working unit, the impurities separation efficiency coefficient, which characterizes the work of the experimental working unit with regard to the separation of large impurities, mainly straw and torn spikelets.

2. As a result of conducting a full factorial experiment, the regression equation was obtained, which establishes the dependence of the efficiency of impurity separation on the specific feed, the oscillation frequency and the diameter of the sieve openings.

3. Verification of the regression coefficients according to the Student's t-test showed that all obtained coefficients are greater than their confidence intervals, which indicates that all coefficients are significant.

4. Verification of the adequacy of the regression model according to Fisher's test revealed that the model was adequate. This allows further research with the given model.

5. As a result of the study of the regression equation for the maximum and the minimum value, it was revealed that the maximum value of the impurities separation efficiency coefficient of 0.912 occurs at the following values of the factors: $x_1 = -1$, $x_2 = -1$ and $x_3 = -1$, which is clearly shown by the constructed response surfaces. In decoded form, this corresponds to the specific feed of $2,1 \text{ kg/s} \cdot \text{m}^2$, the oscillation frequency of 45 s^{-1} and the diameter of the sieve openings of 15 mm.

6. The obtained value of the diameter of the sieve openings equal to 15 mm, which provides the highest value of the impurities separation efficiency coefficient, contradicts the recommended in the paper [11] value of the diameter of the sieve openings equal to 35 mm as

providing the highest efficiency of the separation coefficient. This fact indicates the need for further research.

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