

Article

Efficiency of Combed Straw Harvesting Technology Involving Straw Decomposition in the Soil

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Abstract: This article deals with the problem of harvesting combed straw by mixing it with the soil and the process of combed straw decomposition in particular. The idea and purpose of the research are also analysed in terms of circular economy, which represents a closed cycle. Combed straw is seen as a by-product which is reused as fertilizer to increase soil fertility, thus reducing the negative impact on the environment and increasing the efficiency of organic matter use. To analyse the qualitative aspect of the process, the introduction of an indicator is proposed—the straw decomposition coefficient. Experimental studies of straw decomposition in the soil were carried out using the mathematical theory of experimental design, where the response function is represented by the functional dependence of the straw decomposition coefficient on the length of its cutting and nitrogen and phosphorus application doses. For experimental studies, Box–Behnken design was used, which made it possible to calculate the regression coefficients by known formulas. Verification of the obtained coefficients according to Student’s *t*-test showed that all of them were significant. According to Fisher’s test, it was established that the model is adequate and can be used for further research. As determined by the experimental study, shredded straw incorporation improves soil properties and increases its biological activity. Ultimately, this improves plant nutrition and increases crop yields. The experiment results showed that reduced amounts of nitrogen and phosphorus fertilizers can be applied, thus leading to a reduction in the direct production costs of growing cereals in the following year. The integration of several technological processes, such as straw cutting, shredding, and incorporating it into the soil with simultaneous application of nitrogen and phosphorus fertilizers, increases the economic efficiency of grain production and a shortens the payback period for investment.

Keywords: combed straw; harvesting technology; regression equation; decomposition coefficient; adequacy; response function; circular economy; profitability; economic efficiency

1. Introduction

Grain production in Ukraine is the leading branch of agriculture. However, the harvester park is being reduced significantly, while the area for grains has increased.

Consequently, the load per one harvester has increased. This has led to an interruption of the agricultural harvesting schedule and, as a result, an increase in yield losses and a decrease in the quality of grain. These deficiencies will be addressed by the introduction of grain harvesting by means of combing plants on the stalk. However, the widespread adoption of this technology is constrained by the lack of technology for harvesting combed straw.

This creates an economic problem, the essence of which is the low technical and economic efficiency of the technological process of harvesting combed straw. The solution of this problem is impossible without solving the corresponding scientific and technical tasks, presenting the scientific basis of the technology for harvesting combed straw.

While harvesting grains, after the combing header passes, the combed plant stalks remain uncut. The grain part and an insignificant part of straw are harvested with the chaff, which is a valuable component of the non-grain part of the crop for livestock feed. To complete the harvesting cycle, it is necessary to develop a technology for harvesting combed straw and, at the same time, tackle the problem of increasing soil fertility by mixing it with part of the biological crop. Straw from grain crops incorporated into the arable layer is one of the sources of its replenishment with organic matter.

Therefore, the aim of this study is to increase the efficiency of harvesting the non-grain part of the crop by returning the straw into the soil to increase its fertility.

To achieve this aim, the following research objectives were set:

- To conduct a full factorial experiment;
- To calculate regression coefficients and verification of their significance according to Student's *t*-test;
- To assess the adequacy of the obtained regression equation according to Fisher's test;
- To study the regression equation by methods of mathematical analysis;
- To determine the rational values of factors providing the best conditions for straw decomposition in the soil;
- To develop the technology for harvesting combed straw.

The object of the study is the process of straw decomposition in the soil. The subject of the study is the regularity of the influence of the main factors on straw decomposition in the soil. The mathematical theory of full factorial experiment planning was the basis for the experiments; its results were processed using probability theory and mathematical statistics. Mathematical analysis was used to determine the optimal values of the factors.

As a result, a mathematical model for straw decomposition in the soil has been obtained, which establishes the dependence between the qualitative indicator of the process and the factors influencing it, which allows the technology of harvesting combed straw to be substantiated scientifically. The practical value of the obtained results relies on determining the optimal values of factors influencing the process of straw decomposition.

Today, the primary method of harvesting grains is combining. However, it has significant deficiencies, including high transport costs, the difficulty of harvesting lodged grain, the impossibility of harvesting wet grain mass, etc. Furthermore, the main drawback of the technology is the limited throughput capacity of the threshing and separating devices, which can be increased either by modernizing the device [1] or by enhancing the separation process in the cleaning system of the combine harvester [2]. Alternatively, the process of grain separation in the straw walker of the harvester can be improved [3]. To eliminate the disadvantages of the traditional method, the technology of combing plants on the stalk can be used, presented in [4]. The mentioned technology can be implemented in two variants: the stationary method and the combine harvesting method. The development of the stationary method specifically, designing the working organs for separating the combed heap, is described in [5,6]. The combine harvesting method [7,8] is used by attaching the grinding reaper to the machine. In recent years, a growing number of research papers devoted to harvesting by combing plants on the stalk have emerged. Thus, paper [9] provides com-

parative data on the harvesting of winter wheat seed grain with the use of the traditional combine harvester and the combine equipped with a combing header. According to the authors, the method of combing on the stalk can increase the speed of the harvester, which leads to an increase in its efficiency. The combing header has proven to be effective in humid conditions. In general, the use of this method increases the cost-effectiveness, as well as reduces the production cost of harvesting. The use of the combing header made it possible to increase the economic indicators under high humidity conditions. In the course of the experiment, crop losses in the case of harvesting by combing on the stalk under high humidity decreased by 18–23%. Productivity increase directly affects the reduction in fuel consumption, thus affecting the cost of production.

Similar results proving the efficiency of using combing headers are presented in [8,9]. The results of their research support the argument about the benefits of combing on the stalk method.

Despite the indisputable advantages of harvesting by combing plants on the stalk over traditional technology, one issue remains to be solved, that is, harvesting the combed straw. The problem is that after the passage of the combine equipped with a combing header or a harvesting machine with combing working units, the combed straw is left on the field. From this, the problem of developing a technology for harvesting the non-grain part of the crop arises [10–13]. This poses a need to increase the efficiency of harvesting straw by returning the straw part of the biological crop to the soil to increase soil fertility.

Grain straw incorporated in the arable layer is one of the sources of replenishing the soil with organic matter [14]. However, this raises the problem of identifying the mechanism and factors that affect straw decomposition in the soil. The study of this process is presented in [15–17]. The researchers studied the effect of soil cultivation on the straw decomposition rate. In addition, articles [13,18,19] present the results of studies on the use of shredded straw as fertilizer. The experiments were carried out both with and without biopreparation treatments. Positive results were obtained when straw was treated with biopreparations. The optimum straw decomposition coefficient has been determined, which contributes to the improvement of soil fertility and increases the absolute performance of the experiment.

The impact of plant residue decomposition on the stability of the soil aggregate is described in [20]. Mixing shredded straw with the soil to increase its fertility can be seen in terms of a circular economy, which represents a closed cycle. Straw is a by-product reused as fertilizer in the production of new products, thus reducing the negative impact on the environment and increasing the efficiency of using the organic matter.

However, previous research does not provide a coherent picture of the process. The study of agrobiological processes using cybernetic research methods (modelling) is the basis for the systematic approach to the solution of the set tasks [21–24]. A system analysis method of the process under study includes the appropriate planning of the experiment, the development of the mathematical model, and its further study with the use of computer software [25].

To justify the relevance of the study topic, an analysis of the most used keywords related to “circular economy” and “soil fertility” was conducted. The results of the analysis showed that 63 documents containing the terms “circular economy” and “soil fertility” in the title, abstract, and keywords were indexed in the Scopus database, while about 44% of them were published in 2022. The first article was indexed in Scopus in 2016. This indicates the novelty and relevance of the present research. Using the obtained data, a bibliometric analysis was performed with the help of the VOSviewer program in order to identify the priority research trends in this topic (Figures 1 and 2).

The performed bibliometric analysis (Figure 1) allowed us to identify four research clusters of the terms “circular economy” and “soil fertility”:

1. Cluster 1 (12 words) is marked in red. This cluster mainly focuses on the research of circular economy (35 links), agriculture (34 links), and soils (32 links);
2. Cluster 2 (11 words) is marked in green. This cluster mainly focuses on the study of fertilizer (35 links), biomass (33 links), and chemistry (32 links);
3. Cluster 3 (7 words) is marked in blue. This cluster mainly focuses on the study of the soil amendment (33 links), soil quality (31 links), and carbon (28 links);
4. Cluster 4 (6 words) is marked in yellow. This cluster mainly focuses on researching the soil fertility (35 links), soil (33 links), and plant growth (29 links).

Despite the growing attention to the issue of the development of a circular agricultural economy [26], the implementation of its principles in the agrarian sector is most often considered by scientists from the standpoint of bioenergy utilization of agricultural waste [27], leaving out of the issue of soil fertility recovery.

When used as an organic fertilizer, straw is a valuable source of dry organic matter. It is estimated that 70–100 kg/ha of humus produced from each ton of straw mixed in the soil provides it with a significant amount of nutrients: nitrogen—3.7–5.5 kg, phosphorus—0.8–1, potassium—5.5–11, and calcium—2.2–9.2 kg.

The chronological analysis of the frequency of use of the terms in the formed thematic sample of articles (Figure 2) indicates that the economic aspects of soil fertility together with waste management have been among the most urgent issues within the past two years.

The analysis of the scientific background allowed us to formulate the following hypothesis: it is possible to improve the efficiency of straw decomposition in the soil by optimizing the factors influencing this process, and optimization is achieved by creating a mathematical model and its further analysis. This, in turn, will increase the economic indicators of grain production by reducing the yield losses resulting in lower production costs per unit of area and thus increasing the profitability.

2. Materials and Methods

Ukraine has four agro-climatic zones, seamlessly interspersed. The northwest is a warm area with sufficient moisture; the south-eastern part of Ukraine tends to be warm with average humidity; further to the southeast lies a very warm dry zone; and the entire southern part of the country is located in a moderately hot dry zone. Air temperatures below 0 °C are observed for 1 month in the south and for about 4 months in the north. Recently, the climate in Ukraine has changed dramatically, so it can no longer be considered “moderate continental”. This means a whole complex of problems arises associated with water—or rather, its shortage. Ukraine has one of the lowest endowment indicators of its own water resources among European countries—one thousand cubic meters per capita. Every year, Ukraine loses over 500 million tons of black earth—up to 10 tons of soil is lost per ton of grain produced in Ukraine. Soil erosion rates are increasing; the south-eastern part of the country has already reached desertification levels. The primary method for increasing the yield of grains is the optimization of mineral and, above all, nitrogen plant nutrition conditions. One of the ways to preserve the grain yield and improve its quality is the desiccation of wheat crops in the final stage of cultivation. As a result, the plants are dried and harvested more efficiently.

About 70% of Ukraine’s land is agricultural land, most of which is concentrated on fertile soils and is ploughed. Arable land makes up 4/5 of the total area of agricultural land. The humus layer can reach 120 cm. Both high humus content in the soil (8–15%) and its grainy and lumpy structure contribute to its high fertility.

To obtain the primary information about the process of straw humification, experimental studies were carried out in the demonstration fields of Dmytro Motornyj Tavria State Agrotechnological University (Zelenyi village, Melitopol raion, Zaporizhzhia oblast) (Figure 3).



Figure 3. View of the field after the passage of the harvesting machine with combing working units: (a) millet field, (b) soybean field.

For experimental studies, a non-compositional rotatable three-level Box–Behnken design was chosen. Its distinctive feature is that in all the lines of the design some factors are at zero levels. To carry out the experiment, a matrix of experiment planning (Table 1) was used in which the lower level is marked with “−”, the upper level with “+”, and the middle level with “0”. The experiments were laid in fivefold repetition. To exclude heterogeneities of discrete and continuous types, the experiments were randomized. Randomization of experiments ensures the even application of the element of randomness under the influence of unmanageable and uncontrolled factors on the response. Randomization was performed by using tables of random numbers.

Table 1. Matrix of the non-compositional three-level second-order design for the three factors.

Number of the Experiment	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	x_1^2	x_2^2	x_3^2
1	+	+	+	0	+	0	0	+	+	0
2	+	+	−	0	−	0	0	+	+	0
3	+	−	+	0	−	0	0	+	+	0
4	+	−	−	0	+	0	0	+	+	0
5	+	0	0	0	0	0	0	0	0	0
6	+	+	0	+	0	+	0	+	0	+
7	+	+	0	−	0	−	0	+	0	+
8	+	−	0	+	0	−	0	+	0	+
9	+	−	0	−	0	+	0	+	0	+
10	+	0	0	0	0	0	0	0	0	0
11	+	0	+	+	0	0	+	0	+	+
12	+	0	+	−	0	0	−	0	+	+
13	+	0	−	+	0	0	−	0	+	+
14	+	0	−	−	0	0	+	0	+	+
15	+	0	0	0	0	0	0	0	0	0

The straw of cereal crops contains 15% moisture, as well as 80% organic matter feeding the soil micro-organisms, whose destruction (decomposition) products are the main humus-forming element. Depending on the weather, the cultivation technology, and the soil type, straw contains 35–40% organic carbon, 0.8% potassium, 0.5% nitrogen, 0.25% phosphorus (in anhydride form), 200 g zinc, 150 g manganese, 25 g boron, 15 g copper, 2 g molybdenum, and 0.5 g cobalt.

The experiment was carried out in the field, and for each repetition straw was put to a depth of 0.15 m, the size of the beds was 0.5 × 0.5 m, and the experiment lasted for 8 months (the experiments were laid in September, the results were obtained in April).

The next step in the study was the choice of the response function and factors influencing the decomposition process. The function of change of the straw decomposition coefficient is proposed as the response function. The straw decomposition coefficient is calculated by the formula

$$k_r = \frac{m_s - m_r}{m_s}, \tag{1}$$

where m_s —mass of straw;
 m_r —mass of residues.

The analysis of works [13,18] helped to identify the main factors influencing the process of straw decomposition in the soil—straw cutting length and nitrogen and phosphorus application doses. The experiments were carried out according to the compiled matrix in five replicates, while the regression coefficients were calculated using the known formulas given in [28]. The general form of the regression equation is shown in the equation below:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \tag{2}$$

where x_1 —the length of straw cutting, l, m;
 x_2 —nitrogen application dose, dN , kg/t (kg nitrogen per 1 ton of straw);
 x_3 —phosphorus application dose, dP , kg/t (kg phosphorus per 1 ton of straw);
 y —response function.
 The variation levels of the factors of the experiment are shown in Table 2.

Table 2. Variation levels of factors.

Level Additionally, Range of Variation of Factors	Factors		
	Length of Cutting Straw	Nitrogen Application Dose	Phosphorus Application Dose
	x_1 , m	x_2 , kg/t	x_3 , kg/t
Upper level (+)	0.40	20	6
Middle level (0)	0.30	10	3
Lower level (−)	0.20	0	0
Range of variation	0.10	10	3

The experiments were laid out according to the matrix compiled. The layout of the experiments is shown in Figure 4.



Figure 4. Layout of the experiments in the study of the straw decomposition process.

For each experiment, straw was placed in pre-prepared pits of 0.5×0.5 m at a rate of 6 t/ha (0.15 kg for each experiment) and fertilizers were applied.

The amount of fertilizers and the length of straw were regulated, on the one hand, by the matrix of the experiment (Table 1), and on the other hand, by the levels of variation factors (Table 2).

As an example, let us consider in more detail the layout of the first experiment. For the first experiment, the first two factors are at their upper levels, and the third is at its middle level (Table 1). This means a straw length of 0.4 m, a nitrogen application dose of 20 kg/t (which is 9 g ammonium nitrate per pit), and a phosphorus application dose of 3 kg/t (2.4 g superphosphate per pit). After laying the straw and fertilizing, the pit was covered with soil and a plate with the number of experiences was installed. In the same way, all 15 experiments were laid, with a fivefold repetition of each one. At the end of the experiment (after 8 months), the pits were carefully excavated, the soil was sifted, and the leftover undecomposed straw (Figure 5) was weighed. The decomposition coefficient was calculated using Equation (1).



Figure 5. Leftover undecomposed straw at the end of the experiment.

3. Results and Discussion

As a result of the full factorial experiment, primary information was obtained, which made it possible to calculate the regression coefficients by known formulas using the Optim Box–Benkin software [28,29], the results of the calculations are shown in Table 3.

Table 3. Parameters of the mathematical model.

Name of Model Parameters	Calculated Values
Regression coefficients	$b_0 = 0.915;$ $b_1 = -0.185;$
	$b_2 = 0.170;$ $b_3 = 0.06;$
	$b_{12} = 0.044;$ $b_{13} = 0.043;$
	$b_{23} = 0.041;$ $b_{11} = -0.11;$
	$b_{22} = -0.272;$ $b_{33} = -0.133$
Confidence intervals of regression coefficients	$\Delta b_0 = \pm 0.0471;$ $\Delta b_{i\downarrow} = \pm 0.0407;$
	$\Delta b_i = \pm 0.0292;$ $\Delta b_{ii} = \pm 0.043$
Variance of reproducibility	$S^2\{y\} = 0.00037$
Variance of adequacy	$S^2_{ad} = 0.0007$
Calculated value of Fisher’s test	$F_c = 1.971$
Tabulated value of Fisher’s test	$F_t = 19.3$ model is adequate

After determining the regression coefficients, their significance was verified by known formulas given in [29] according to the following method:

- Variance characterizing the error of the experiment was determined;
- Variance of reproducibility by the results of the experiments in the centre of the design was calculated;
- Variances characterizing the errors in determining the coefficients of the regression equation were found;
- The confidence interval of the regression coefficients was calculated using Student's *t*-test, which is found from the tables, in our case it is 4.3;
- Confidence intervals are compared to the values of regression coefficients.

The following values of confidence intervals were obtained from the calculations (shown in Table 3).

The numerical values of the regression coefficients were larger than their confidence intervals. This leads to the conclusion that all regression coefficients are significant.

Thus, the regression equation has the following form:

$$y = 0.915 - 0.185x_1 + 0.170x_2 + 0.06x_3 + 0.044x_1x_2 + 0.043x_1x_3 + 0.041x_2x_3 - 0.11x_1^2 - 0.272x_2^2 - 0.133x_3^2. \quad (3)$$

The adequacy of the resulting model is verified by the *F*-test. For this purpose, F_c is found from the table and compared with F_t ; in this case, this was the calculated value $F_c = 1.971$, and the tabulated value $F_t = 19.3$. Therefore, $F_t > F_c$ —the model is adequate at a 5% significance level. The results of calculating the regression coefficients and statistical analysis of the regression equation are shown in Table 3.

By implementing the second-order design and subsequent coefficient calculations, a mathematical model was obtained in the form of a second-degree polynomial that adequately describes the optimum area. In this form, the second-degree equation is difficult to analyse, so by means of transformations it can be brought to the canonical form.

The canonical transformation of the second-degree equation consists of choosing a new coordinate system in which the equation takes a more simple form. A new coordinate system is obtained by the parallel transfer of the old system to a new origin and the rotation of the coordinate axes with respect to this origin. As a result, the regression equation is reduced to the standard canonical equation:

$$Y - Y_S = B_{11}X_1^2 + B_{22}X_2^2 + \dots + B_{kk}X_k^2 \quad (4)$$

where Y —value of the optimization parameter;

Y_S —value of the optimization parameter in the new origin of coordinates;

X_1, X_2, \dots, X_k —canonical variables representing linear functions of the factors;

$B_{11}, B_{22}, \dots, B_{kk}$ —coefficients of the regression equation in the canonical form.

The first stage of the canonical transformation is moving the origin of coordinates to a specific point—the centre of the response surface. To determine the coordinates of this point, the original equation is differentiated with respect to each independent variable:

$$\begin{aligned} \frac{\partial y}{\partial x_1} &= -0.185 + 0.044 \cdot x_2 + 0.043 \cdot x_3 - 0.22 \cdot x_1; \\ \frac{\partial y}{\partial x_2} &= 0.170 + 0.044 \cdot x_1 + 0.041 \cdot x_3 - 0.544 \cdot x_2; \\ \frac{\partial y}{\partial x_3} &= 0.060 + 0.043 \cdot x_1 + 0.041 \cdot x_2 - 0.266 \cdot x_3. \end{aligned} \quad (5)$$

By equating partial derivatives to zero and having made algebraic transformations, we obtain a system of three linear equations:

$$\begin{cases} -0.185 + 0.044 \cdot x_2 + 0.043 \cdot x_3 - 0.22 \cdot x_1 = 0; \\ 0.170 + 0.044 \cdot x_1 + 0.041 \cdot x_3 - 0.544 \cdot x_2 = 0; \\ 0.060 + 0.043 \cdot x_1 + 0.041 \cdot x_2 - 0.266 \cdot x_3 = 0. \end{cases} \quad (6)$$

We find the determinant of this system, which is $\Delta = -0.0297$. The determinant of the system is nonzero; therefore the response surface has a centre. The centre coordinates were found by solving Equation system (6). Their numerical values are equivalent to $X_{1S} = -0.767$, $X_{2S} = 0.266$, and $X_{3S} = 0.155$, respectively. The value of the optimization parameter Y_S at the new origin of coordinates $Y_S = 1$ was defined by substituting the values of X_{1S} , X_{2S} , and X_{3S} . After the parallel translation of the coordinate axes, the equation takes the following form:

$$y = 1 + 0.044\tilde{X}_1\tilde{X}_2 + 0.043\tilde{X}_1\tilde{X}_3 + 0.041\tilde{X}_2\tilde{X}_3 - 0.11\tilde{X}_1^2 - 0.272\tilde{X}_2 - 0.133\tilde{X}_3 \quad (7)$$

where \tilde{X}_1 , \tilde{X}_2 , and \tilde{X}_3 are new coordinates.

To determine coefficients B_{11} , B_{22} , and B_{33} , the following characteristic equation was solved:

$$f(B) = \begin{vmatrix} b_{11} - B & \frac{1}{2}b_{12} & \frac{1}{2}b_{13} \\ \frac{1}{2}b_{21} & b_{22} - B & \frac{1}{2}b_{22} \\ \frac{1}{2}b_{31} & \frac{1}{2}b_{32} & b_{33} - B \end{vmatrix} = 0. \quad (8)$$

By substituting the values of b_{11} , b_{12} , b_{13} , the following was obtained:

$$f(B) = \begin{vmatrix} -0.11 - B & \frac{1}{2} \cdot 0.044 & \frac{1}{2} \cdot 0.043 \\ \frac{1}{2} \cdot 0.044 & -0.272 - B & \frac{1}{2} \cdot (-0.272) \\ \frac{1}{2} \cdot 0.043 & \frac{1}{2} \cdot 0.041 & -0.133 - B \end{vmatrix} = 0. \quad (9)$$

By revealing the determinant (9), a cubic equation of the following form was obtained:

$$B^3 + 0.515 \cdot B^2 + 0.08 \cdot B + 0.0035 = 0. \quad (10)$$

Its roots were found by solving this cubic equation:

$$B_{11} = -0.256; B_{22} = -0.186; B_{33} = -0.073.$$

The correctness of the calculations was verified by comparing the sum of the coefficients at quadratic terms in the reference equation and the canonical equation:

$$\sum_{l \leq i \leq k} b_{ii} = \sum_{l \leq i \leq k} B_{ii}. \quad (11)$$

Since the equation is satisfied, we can conclude that coefficients B_{11} , B_{22} , and B_{33} have been determined correctly. Thus, Equation (3) in the canonical form has the following form:

$$Y - 1 = -0.256 \cdot X_1^2 - 0.186 \cdot X_2^2 - 0.073 \cdot X_3^2.$$

Therefore, movement to either side from the centre decreases the optimization parameter, i.e., there is a maximum with the coordinates of the centre $X_{1S} = -0.767$, $X_{2S} = 0.266$, and $X_{3S} = 0.155$. Based on the results obtained, the factors have the following values: straw cutting length $l = 0.22$ m, nitrogen application dose $dN = 12.66$ kg/t, and phosphorus application dose $dP = 3.47$ kg/t.

Thus, the studies of straw decomposition in the soil and their further analysis have led to the development of a technology for harvesting combed straw, the block diagram of which is shown in Figure 6.

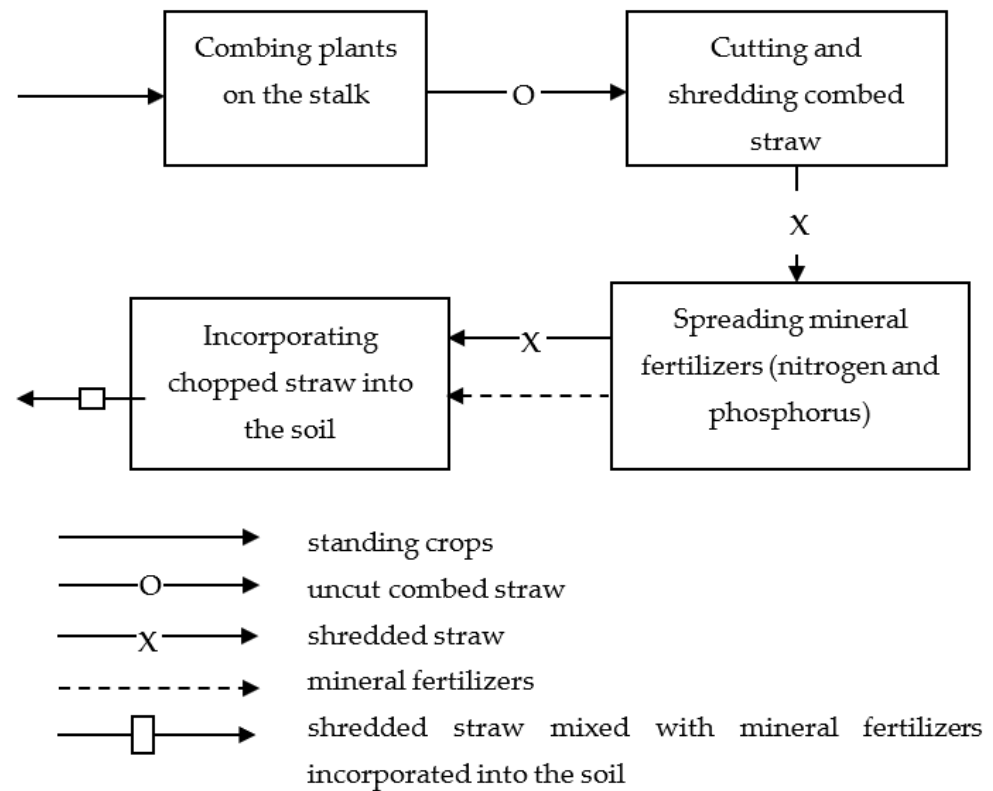


Figure 6. Block diagram of harvesting combed straw.

Let us consider the straw harvesting technology with a harvesting unit (Figure 7) (a tractor, a harvester equipped with a grinder, and a trailer-cart for collecting the combed heap). After the passage of the unit, the grain part of the crop is combed and supplied by the pneumatic conveyor to the trailer-cart, and the combed stalks are left in the field (combed straw, Figure 3). To harvest them, a rotary cutter is provided, which is mounted on the harvester. Its main purpose is to cut, grind, and scatter the combed stalks over the field. As a result, combed stalks of plants 0.22 m long are left in the field.



Figure 7. General view of the harvesting unit.

The field remains in this form until the basic soil treatment begins. The scattered shredded straw preserves moisture. This is very important for the southern regions, where a strong drying of the soil is observed after harvesting.

Before straw is incorporated into the soil, it is necessary to disperse nitrogen and phosphorus fertilizers at the rate of 12.0–12.7 kg nitrogen and 2.5–3.5 kg phosphorus per 1 ton of straw. The application of mineral fertilizers, as well as shredding to the optimal length, contributes to straw decomposition in the soil.

The obtained experimental results enabled us to perform the following studies of cost-effectiveness of grain production using the method under research.

In the year of the experiment, 78 hectares were allocated to millet at the university's training ground in crop rotation. The test area covered 10 hectares. The crop was grown according to the technological requirements. The results of the research obtained using the proposed harvesting method of combing crops on the stalk proved to be quite promising.

The use of the combing header, due to reduced crop losses while harvesting, increased the yield per 1 hectare of the pilot site to 27.4 q/ha. At the same time, on another plot, when harvested using the traditional method, the yield was 23.2 q/ha. The production costs per hectare of land were the same for both plots. The efficiency of the harvesting unit with a combing header was found to increase in the course of the experiment. This trend has led to a decrease in fuel consumption per hectare of harvested land of 0.6 kg/ha, which equals 3.2%.

The effect indicators obtained by applying the proposed harvesting method were reflected in the dynamics of the economic efficiency indicators for the use of the described harvesting unit. For example, by reducing direct fuel expenses, production costs per hectare of the experimental plot were reduced by 0.4%. However, significant experimental dynamics can be observed in relative indicators, thus showing the success of the research. A reduction in harvesting losses and, consequently, an increase in yields has led to a decrease in the cost of production. Results analysis shows that in the course of the research, there has been a decrease in production costs per 1 q by 15.6% compared to the same indicator observed at the non-experimental plot.

The main applicability factors of the proposed harvesting method are the reduction in direct material costs per 1 hectare of harvested area, the reduction in the production cost and, as a result, the full cost of the grown produce, and an increase in yields, which is driven by reduced crop losses resulting from the use of the experimental unit. The combination of these indicators made it possible to achieve an increase in profitability per 1 hectare of harvested area, with a profit increase of 49.2% per 1 hectare of harvested area, and the profitability level was 25.5% higher compared to the non-experimental plot.

Thus, the feasibility of the proposed method of combing crops on the stalk has been proven. This is confirmed by the economic indicators of the study. While combing on the stalk, straw is shredded to a certain size and later used as a fertilizer in combination with the experimentally obtained doses of nitrogen and phosphorus fertilizers. Further use of shredded straw as a nitrogen fertilizer for next year's harvest is one of the tools of a circular economy. The closed-loop economy is based on recycling. Thus, a circular economy offers a more rational approach to the use of resources and to dealing with waste and secondary raw materials.

The experiment concerning the efficiency of the use of shredded straw as fertilizer continued the following year. The shredded straw, together with the necessary fertilizers, was incorporated into the surface soil for next year's harvest. The experimental area covered 10 hectares. The studied crop was winter wheat. Millet straw was used at the rate of 2.65 t/ha, with doses of 32.9 kg nitrogen and 9.19 kg phosphorus fertilizers per 1 ton of straw, which would provide the necessary straw decomposition rate to increase the fertility of the surface soil. Later, when growing winter wheat, these doses of fertilizers were taken into account. In the course of the experiment, positive results were observed during the seedbed care period in the germination of seeds and the shooting and tillering of the crops.

At the end of the experiment, the following results were obtained. On the experimental plot, yields increased by 2.7 q per 1 ha. At a constant value of production costs, the decrease in the cost of production of the crop was 6.6%. As a result of the proposed method of incorporating shredded straw into the soil with simultaneous application of fertilizers, the profit growth rate per 1 quintal of grain was 21.7%, and per 1 hectare of harvested area was 30.4%. The profitability of winter wheat cultivation by applying the experimental technology increased from 30.4% to 39.6%.

4. Conclusions

A full-factorial experiment has been carried out, for which a non-composition rotatable three-level Box–Behnken design has been chosen. Straw decomposition rate has been used as the response function, and the length of straw cutting and the nitrogen and phosphorus application doses have been taken as factors. A mathematical model was proposed and tested. The related coefficients inferred with regressions derived from the experimental data. The statistical significance of these regressions was studied by applying a Student's *t*-test analysis. Both these regressions and the statistical analysis were performed by using computer software. All coefficients were found significant. As a result of experimental studies of the process of combed straw decomposition in the soil, a regression model was obtained which establishes the relationship between the qualitative indicator of the process and the main factors affecting it.

Verification of the adequacy of the obtained regression model according to Fisher's test showed that the calculated value is $F_c = 1.971$, and the tabulated value is $F_t = 19.3$; therefore, $F_t > F_c$, which shows that the model is adequate and can be used for further analysis. The study of the regression equation by methods of mathematical analysis revealed that the maximum value of the combed straw decomposition coefficient is observed at the straw cutting length of 0.22 m, the nitrogen application dose of 12.66 kg/t, and the phosphorus introduction dose of 3.47 kg/t. The obtained results of the experimental studies have made it possible to develop a technology for harvesting combed straw.

Shredded straw incorporation, as determined by the experimental study, improves soil properties and increases soil biological activity. Ultimately, this affects improved plant nutrition and, as a result, increases crop yields.

Overall, the results of the study can be divided into two efficiency groups:

1. Technological efficiency indicators—reduction in grain loss when harvesting with a combing header, which gives an increase in yield up to 4.2 q/ha; improved quality of the fertile soil layer by mixing ground straw and partially saturating the soil with nitrogen and phosphorus fertilizers for next year's crop; due to the specific features of the experimental plant, an increase in the productivity of the harvester and a reduction in the harvesting time are observed.
2. Economic efficiency indicators—cost-effective reflection of the technological efficiency indicators of the experiment. By reducing the yield losses and, as a result, increasing the yield, the amount of additional profit from 1 hectare is determined by the current price in the calculated year, while the value of production costs remains unchanged. Increased unit productivity (reduced fuel consumption by 0.6 kg/ha) compared to the cost of the production material results in lower production costs per unit of area and a similar change in the cost of production of 1 quintal of the crop. In terms of circular economy, besides the increase in the yield of next year's grain crops, the use of shredded straw eventually redistributes the amount of fertilizer input for the next period.

The conducted study revealed the positive economic results of the presented method of harvesting cereals, which indicate the appropriateness of its use. The harvesting method by combing on the stalk with further use of shredded straw as a fertilizer is considered as one of the solutions to the problem of using by-products, which is one of the challenges that the circular economy is addressing. The results of the experiment confirm that the use of shredded straw as a fertilizer allows for an increase grain yield of 7.1%.

Studies have shown that the use of the combing header will reduce crop losses while harvesting, which increases yields and reduces production costs. As a result, an increase in profits per unit of area and output is observed and, consequently, an increase in the profitability of crop cultivation is also achieved.

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