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JUSTIFICATION OF THE AREA AND PARAMETERS OF STRAW EMISSION BY WORKING BODIES OF A GRAIN HARVEST SPREADER WHEN HARVESTING LOW YIELD GRAIN CROPS

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Abstract

The uniform distribution of chopped straw across the working width of the headers of 9–12 m posed a significant production challenge during grain harvesting in the conditions of the northern region of Kazakhstan. Research methods included theoretical and experimental studies. It was found that in order to increase the width and reduce the uneven spread of the chopped mass over the field, it is necessary to ensure that the initial speed of the chopped straw ejection is 63 m/s and the angle of inclination of the trajectory of the chopped mass to the horizon is about 15 degrees; and the ejection of the chopped mass should be carried out from the fourth sector of the left spreader and the third sector of the right spreader, closer to the periphery of the radius. Based on the results obtained, a low-energy straw spreader was developed and tested. It has been established that with a straw moisture content of 10–20%, the developed spreader provides a maximum spread width of 12–10 m, respectively, a distribution unevenness of 19–27%, and a chopping length of 23–25 cm.

Keywords: soil mulching with straw, straw ejection area in the spreader, initial spread speed, initial angle of inclination of the trajectory, spreading width and unevenness

INTRODUCTION

In the northern region of Kazakhstan, up to 75% of the republic's grain is produced. In the conditions of the arid steppe region, during cultivation, it is necessary to apply measures to reduce the loss of soil moisture and reduce wind erosion, increase organic material in the soil, improve its structure and reduce density. Such measures include mulching the soil with straw during harvesting.

It is known that leaving stubble and shredded plant residues is considered an effective measure against erosion. Straw mulch counteracts the damaging effects of rain and wind on the soil (Straw as a fertilizer and its role in increasing soil fertility, 2003; Vadas P. *et al.*, 2014). Straw mulching retains moisture in the soil by reducing evaporation (Abbas E. *et al.*, 2014; Yanqun Zhang *et al.*, 2021). Straw and other plant residues improve soil structure, soil aeration. Straw mulch from plant residues helps to reduce soil density and soil crust, and improve soil drainage (Acharya C. L. *et al.*, 2018; Acharya C. L. *et al.*, 2005; Advanced Remote Sensing, 2012). Straw and other plant residues increase the content of organic matter in the soil and contribute to CO_2 fixation in the soil (Huang Wan *et al.*, 2021; Kashif Akhtar *et al.*, 2019; Jianwei Zhang *et al.*, 2021; Yang Qu *et al.*, 2020; Kashif Akhtar *et al.*, 2020; Wenjun Xie *et al.*, 2021). The application of straw mulch increases the content of nitrogen, phosphorus, and potassium in the soil (Han, Y. *et al.*, 2021; Xu, C. *et al.*, 2015). The application of straw promotes the growth of microorganisms in the soil and provides an increase in crop yields (Shi, Y. *et al.*, 2021).

However, at present, insufficient attention is paid to the issue of soil mulching with straw. When harvesting, the straw is most often placed in swaths, which are burned in the spring. The main reasons for this are: insufficient straw spreading width (4–6 m) with a harvester width of 9–12 m; large uneven spread of chopped straw; a decrease in the productivity of a combine harvester and an increase in fuel consumption during chopping and spreading straw.

We have analyzed the designs of mounted straw choppers and systems for spreading chopped straw and chaff for modern combine harvesters of the world's leading companies (Skorlyakov, V. I., 2013; Rybalkin, P. N. *et al.*, 2001; Yagelsky, M. Y., Rodimtsev, S. A., 2016; New Holland Agriculture, 2021; Massey Fergusson, 2021; Claas, 2021; John Deere, 2021; Sampo Rosenlew, 2021; Deutz Fahr, 2021; Fendt, 2021; Rodimtsev, S. A., Yagelsky, M. Y., 2013). All structural and technological schemes of technical devices for chopping and spreading straw can be divided into three groups:

- shredders with passive guide deflectors for spreading chopped straw;
- choppers with additional active radial spreaders of chopped straw;
- active radial straw spreaders.

The first and second groups of technical devices are designed for chopping and spreading long-stalk high-yielding straw. The third group of technical devices is designed for chopping and spreading short-stalk, low-yielding straw. However, they do not meet the requirements for the quality of chopping and the quality of straw spreading in the zonal conditions of Kazakhstan. With the working width of the headers of 9–12 m, the chopped straw is spread across 4–6 m, and very unevenly. After the combine passes, local piles of straw remain on the field. This causes clogging of the coulters of the seeders during sowing. To avoid clogging of the coulters, straw is evenly distributed over the field by harrowing.

In the conditions of the region, when harvesting short-stalk, low-yielding grain crops, spreaders with a straw spread width of 9–12 m are necessary to ensure the uniform distribution of straw over the field. The problem lies in the absence of such spreaders for combine harvesters with wide headers.

The purpose of the research is to improve the technological and technical performance of the straw spreader to the combine harvester in the zonal conditions of the region.

Object of study: the technological process of spreading chopped straw by a combine harvester.

MATERIALS AND METHODS

Material characteristics. The average yield of wheat grain in arid zonal conditions is about 1.2 t/ha, varying in the southern and northern regions from 0.7 t/ha to 2.0 t/ha. Low-growing varieties of wheat are grown here with a ratio of grain mass to straw mass as 1 : 1.1. Straw yield under these conditions ranges from 0.8 t/ha to 2.2 t/ha. The height of wheat stalks is from 30 cm to 50 cm.

Research methods included:

- theoretical studies to establish the dependence of the chopped straw spread width on the initial parameters of its release (initial speed and initial angle of inclination of the trajectory to the horizon);
- laboratory and field studies to establish the influence of the initial ejection parameters on the width and uneven spread of chopped straw, as well as its chopping length;
- testing the developed spreader for a combine harvester.

Laboratory and field studies were carried out on a combine harvester with a laboratory installation installed on it, to study initial parameters: the initial speed and the straw ejection area, and the initial angle of inclination of the trajectory of the chopped straw to the horizon. There is a complete three-factor experiment in which each factor changed on two levels (plan 2^3).

The experimental plan is presented in Tab. I.

I: *Full factor experiment plan 2^3*

No	Factors		
1	A_1	B_1	C_1
2	A_1	B_1	C_2
3	A_1	B_2	C_1
4	A_1	B_2	C_2
5	A_2	B_1	C_1
6	A_2	B_1	C_2
7	A_2	B_2	C_1
8	A_2	B_2	C_2

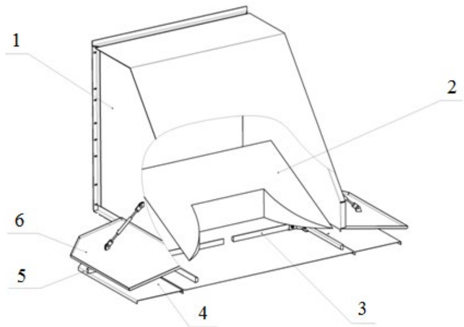
The acting factors and their levels of variation are presented in Tab. II.

In the course of experiments on the laboratory installation, various parameters of initial factors shown in the table were set, depending on which the output indicators were determined: the width and uneven spread of the chopped straw, as well as its chopping length. Since the factor «A» is qualitative and cannot be expressed by quantitative value, then the obtained results were processed by the method of dispersion analysis (Dospekhov, B. A., 1965).

As a result of the theoretical and laboratory-field studies, the feeding area and the parameters of straw ejection by the working bodies of the

II: *Factors and their levels of variation*

Acting factors	Notation	Levels of variation of the factors	
		Lower Level	Upper Level
		Factor value	Factor value
Chopped straw ejection area	A	From the fourth sector of the left and third sector of the right spreader, along the horizontal line connecting the axes of rotation of the working bodies (A_1) (Fig. 4)	From the fourth sector of the left and third sector of the right spreader, closer to the periphery of the radius of the working bodies (A_2) (Fig. 5)
Initial ejection speed of the chopped mass, m/s	B	20 (B_1)	63 (B_2)
Initial angle of inclination of the chopped mass trajectory to the horizon, deg	C	0 (C_1)	15 (C_2)



a) – spreader design


b) – general view

1: *Experimental straw spreader*
1 – hood; 2 – guide shield ; 3 – working body; 4 – air duct; 5 – bottom shield; 6 – upper shield

spreader were substantiated. Then the drawing and technical documentation was developed and an experimental straw spreader for a grain harvester was manufactured (Fig. 1).

Experimental studies of the developed straw spreader were carried out in Zhanakhay LLP in the Kostanay region in comparison with analogues: mounted straw spreaders RS-2M and RPO-1. The quality of work of straw spreaders was assessed in accordance with the requirements for the technological operation “Direct combining of grain crops with chopping and spreading of the non-grain part on the field surface” (Aniskin, V. I. *et al.*, 2005).

Depending on the initial parameters, the following indicators of the technological process were determined:

- spread width of the chopped mass;
- coefficient of variation of chopped mass across the spread width (uneven spread of the chopped straw);
- length of straw chopping;
- productivity losses of a combine harvester during chopping and spreading of straw mass.

The spread width of chopped straw mass was determined by two passes of the combine harvester (one way and back) of 50 m each. On each pass, the current width of the chopped straw spread was measured in five repetitions. Then, the average width of the chopped mass spread was calculated in the surveyed area.

The unevenness of chopped straw spreading was determined as follows. The chopped straw mass was collected at every meter along the spread width in a frame with an area of 1 m^2 and weighed. Then, the average value, the standard deviation and the coefficient of variation across the width of the spreading were determined. Three repetitions were performed in two passes of the combine (one way and back).

The straw chopping length was determined using the following method. Samples were taken across the entire width of the straw spread, in a frame with an area of 1 m^2. Then, the straw was divided by length into fractions and weighed. The average length of each fraction and its mass fraction were determined. Measurements were carried out with three repetitions in two passes of the combine (one way and back). Then, the average value of the chopping length was calculated.

The performance evaluation was carried out in accordance with the requirements of the standard for combine harvester testing, by conducting time-motion studies (GOST 28301-2007. Combine harvesters. Test methods). The time-motion studies were conducted within three standard shifts, each lasting seven hours, with the straw spreader being

either activated or deactivated. The following information was recorded during the observations:
- date and location of the tests, type of work, and composition of the unit;
- description of the area;
- travel speed, working width;
- amount of work performed in hectares;
- duration of time elements within a shift.

Productivity per hour of shift time is calculated using the formula:

$$W_{sh} = W_0 \times K_{sh}, \quad (1)$$

where
W_0 ....productivity per hour of main time;
K_{sh} .... coefficient of utilization of shift time.

The coefficient of utilization of shift time was calculated based on the duration of work elements (working passes, turns, unloading of grain, etc.) of the performed time-motion studies.

Losses in shift productivity of the combine harvester during chopping and spreading of straw mass, were determined using the formula:

$$v = (1 - W_2/W_1) \times 100\%, \quad (2)$$

where
W_1 ....shift productivity of the combine harvester when forming straw swaths, ha/h;
W_2 ....shift productivity of the combine harvester with the straw spreader activated, ha/h.

RESULTS

Analysis of Performance Indicators of Technical Devices for Spreading and Chopping Straw

We have analyzed the performance indicators of known technical devices for spreading and chopping straw (Tab. III) (Skorlyakov, V. I., 2013; Rybalkin, P. N. *et al.*, 2001; Yagelsky, M. Yu., Rodimtsev, S. A., 2016; Rodimtsev, S. A., Yagelsky, M. Y., 2013; Aniskin, V. I. *et al.*, 2005; Skorlyakov, V. I., Yurina, T. I., 2015).

At a low yield of grain straw and with minimal productivity losses, the most preferable option is structural scheme 3. The possibility of energy saving in this option is also confirmed by studies in (Korn C., *et al.*, 2012). However, the quality indicators of this group of spreaders do not meet regulatory requirements. A more detailed analysis gives grounds to assume that the known spreaders of the structural scheme 3 do not have the optimal parameters for spreading straw by the working bodies. Thus, for a group of spreaders according to scheme 1 with the Redecop “Maximum Air Velocity” system, installed on New Holland, Lexion, John Deere combines, the air flow rate at the chopper outlet is 49 m/s (Yagelsky, M. Yu., Rodimtsev, S. A., 2016). Due to the high speed, a spread width of up to 9 m is provided. When using active spreaders according to scheme 2, the ejection speed is even higher. Linear speed of the working bodies of shredders-spreaders of leading companies is 60–88 m/s. This causes a spread width of up to 13.7 m. These spreaders have the ability to adjust the initial angle of inclination of the trajectory of chopped straw to the horizon. For spreaders of structural scheme 3, the linear speed of the working bodies is up to 15–20 m/s. The initial angle of inclination of the chopped straw trajectory to the horizon is not adjustable and is 0 degrees. The analysis conducted made it possible to put forward a hypothesis that an increase in the width of the spread and a decrease in the unevenness of the spread and length of chopping can be achieved by optimizing the parameters of the descent of the chopped straw from the active radial spreader: the initial speed and the initial angle of inclination of the chopped straw trajectory to the horizon.

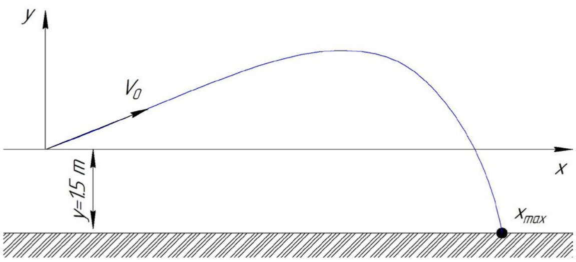
Theoretical Studies to Establish the Dependence of the Chopped Straw Spread width on the Initial Parameters of Its Release

Let's assume that chopped straw stalks are spread by a spreader blade at a speed V_o at an angle α to the horizon. The calculation scheme for determining the flight range of chopped stems is shown in Fig. 2.

When leaving the working bodies, the chopped stems have an initial speed v_0, depending on the

III: *Main agrotechnical and operational indicators of known technical devices for spreading and chopping straw*

Indicators	Standard value	The value of the indicator for the group		
		Structural scheme 1 (chopper with passive deflectors)	Structural scheme 2 (chopper + additional active radial spreader)	Structural scheme 3 (active radial spreader)
Chopping length, cm	≤ 10 [29] ≤ 30 [18]	5–12	5–12	30–40
Spread width, m	≥ (9–12)	4–9	9–13.7	4–6
Spread unevenness, %	≤ 20	Up to 80	33–48	Up to 67
Loss of productivity during straw chopping and spreading, %	≤ 15	Up to 20	Up to 25	Up to 5



2: *Calculation scheme for determining the chopped mass spread width*

blade rotation speed. Immediately after leaving the working bodies, the air resistance force will act on the chopped stems. Let's compose a system of equations of motion of the culm in the XOY coordinates

$$\begin{cases} \Sigma F_x = m \times \ddot{x} = -k \times \rho \times s \times v^2 = -k \times p \times s(\dot{x})^2 \\ \Sigma F_y = m \times \ddot{y} = -m \times g \end{cases} \quad (3)$$

where
p........air density, kg/m³;
m.......straw weight, kg;
k........aerodynamic coefficient of air resistance;
v........straw speed, m/s;
s.........straw midsection area, m²;
$\ddot{x}$, $\ddot{y}$....straw acceleration along the OX or OY axis, m/s²;
g........free fall acceleration, m/s²;
α........the angle of inclination of the working bodies and the flight path of the straw to the horizon, rad.

Let's transform the system:

$$\begin{cases} \ddot{x} = -\dfrac{k \times \rho \times s}{m} \times (\dot{x})^2 = -k_n \times (\dot{x})^2 \\ \ddot{y} = -g \end{cases} \quad (4)$$

where
k_n.......windage ratio.

Let $\dot{x} = v_x$, then $\ddot{x} = \dfrac{dv_x}{dx} \times v_x$

Let $\dot{y} = v_y$

Let substitute these values into (4) system:

$$\frac{dv_x \times v_x}{v_x^2} = -k_n \times dx = \frac{dv_x}{v_x} \quad (5)$$

$$v_y = -g \times t + c_1 \quad (6)$$

From expression (6) we determine y:

At $t = 0$ we obtain $v_{y0} = v_0 \times \sin\alpha$,

Then:

$$c_1 = v_0 \times \sin\alpha$$

and

$$v_y = v_0 \times \sin\alpha - g \times t \quad (7)$$

From expression (5):

$$\ln v_x = -k_n \times x + \ln c_2 \quad (8)$$

or

$$\ln v_x = \ln e^{-k_n x} + \ln c_2 \quad (9)$$

By potentiating, we obtain:

$$v_x = c_2 \times e^{-k_n x}. \quad (10)$$

Under initial conditions $x = 0$, then:

$$v_{x_0} = v_{x_0} \times \cos\alpha. \quad (11)$$

Taking into account:

$$v_x = v_0 \times \cos\alpha \times e^{-k_n x}, \quad (12)$$

$$\frac{dx}{dt} = v_0 \times \cos\alpha \times e^{-k_n x}, \quad (13)$$

or

$$e^{k_n x} \times dx = v_0 \times \cos\alpha \times dt. \quad (14)$$

Integrating over time, we obtain:

$$\frac{1}{k_n} \times e^{k_n x} = v_0 \times \cos\alpha \times t + c_3. \quad (15)$$

Determine c_3 at $t = 0$ and $x = 0$:

$$c_3 = \frac{1}{k_n}. \quad (16)$$

Taking into account:

$$\frac{1}{k_n} \times e^{k_n x} = v_0 \times \cos\alpha \times t + \frac{1}{k_n}. \quad (17)$$

Multiply by k_n:

$$e^{k_n} = v_0 \times \cos\alpha \times k_n \times t + 1. \quad (18)$$

Integrate the expression (15):

$$y = (v_0 \times \sin\alpha) \times t - \frac{g \times t^2}{2} + c_4. \quad (19)$$

Under the initial conditions $t = 0$, we get $c_4 = 0$.

Then from (18) and (19) we obtain the system:

$$\begin{cases} e^{k_n x} = v_0 \times \cos\alpha \times k_n \times t + 1 \\ y = (v_0 \times \sin\alpha) \times t - \dfrac{g \times t^2}{2} \end{cases} \quad (20)$$

From the first equation (20):

$$t = \frac{e^{k_n x} - 1}{k_n \times v_0 \times \cos\alpha}. \quad (21)$$

We substitute (21) into the second equation (20):

$$y = \frac{v_0 \times \sin\alpha(e^{k_n x} - 1)}{v_0 \times \cos\alpha \times k_n} - \frac{g(e^{k_n x} - 2e^{k_n x} + 1)}{2k_n^2 \times v_0^2 \times \cos\alpha^2} =$$

$$= \frac{\mathrm{tg}\alpha(e^{k_n x} - 1)}{k_n} - \frac{g(e^{2k_n x} - 2e^{k_n x} + 1)}{2k_n^2 \times v_0^2 \times \cos\alpha^2} \quad (22)$$

By setting y = -1.5 m and changing the variable:

$$z = e^{k_n x} - 1, \quad (23)$$

we obtain a quadratic equation with variable z, solving which we find the required unknown. Having made the reverse change of variable according to the formula (23), we find x_{max} (Fig. 2):

$$x_{max} = \frac{\ln\left(\frac{\mathrm{tg}\alpha \times k_n \times v_0^2 \times \cos\alpha^2 + k_n \times v_0 \times \cos\alpha \times \sqrt{\sin\alpha^2 \times v_0^2 + 3 \times g}}{q} + 1\right)}{k_n} \quad (24)$$

By setting the values of the abscissa from 0 to x_{max}, we determine from the formula (22) the values of the ordinate y. According to the coordinates y and x, it is possible to create the trajectory of the movement of the chopped straw after leaving the working bodies of the spreader.

The spread width of the chopped straw mass is determined by the formula:

$$B = 2x_{max} + L, \quad (25)$$

where

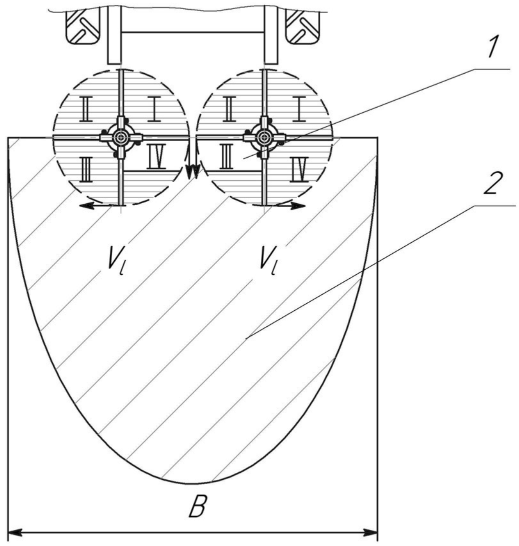
L........distance between the axes of the working bodies of the spreader, mm.

Fig. 3 shows the dependence of the spread width on the initial angle of inclination of the trajectory to the horizon and the initial spread speed of the chopped straw mass from the spreader.

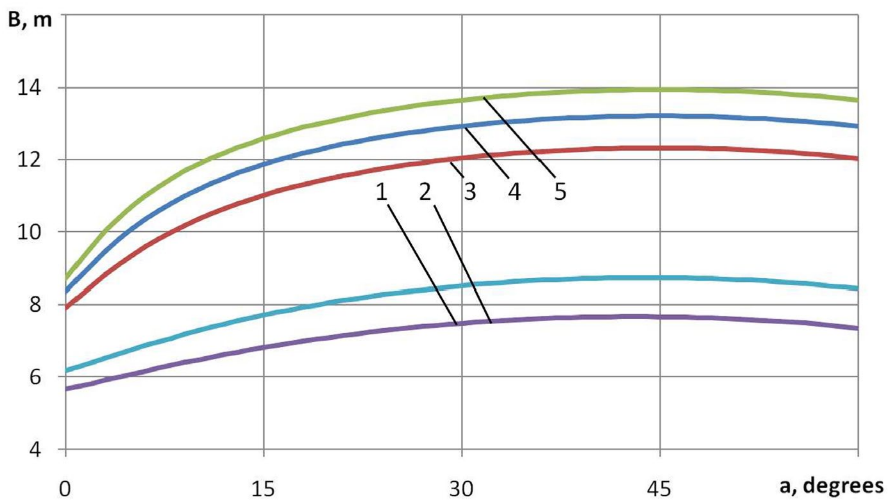
The presented dependencies show that at initial speed of ejection V_0 = 50–75 m/s and initial angle of inclination of the trajectory to the horizon α = 15–45 degrees, the calculated value of the spreading width of the chopped straw is 12–14 m.

The Relationship Between the Feeding Straw Area to the Working Bodies of the Spreader and the Spread Area of the Chopped Mass

Consider the scheme of work of the analogue – straw spreader RPO-1 (Fig. 4).



4: *Chopped straw ejection areas in the RPO-1 spreader and its spreading on the field*
1 – Straw ejection area in the spreader
2 – Chopped straw spreading area on the field



3: *Dependence of the spread width B on the initial angle of inclination of the trajectory to the horizon α and the initial spread speed of the chopped straw mass from the spreader V_0*
1 – V_0 = 15 m/s; 2 – V_0 = 20 m/s; 3 – V_0 = 50 m/s; 4 – V_0 = 63 m/s; 5 – V_0 = 75 m/s

IV: *Influence of the area and parameters of the ejection on the width, uneven spread of straw and its chopping length (fragment)*

Levels of variation of initial factors	Output indicators		
	L_1 – average spread width of the chopped straw, m	L_2 – unevenness of the spread of the chopped straw, %	L_3 – average chopping length of the straw, cm.
Lower level of variation: • A_1 • B_1 • C_1	4.9	60.0	23.7
Upper level of variation: • A_2 • B_2 • C_2	11.6	17.7	20.1

From the keys of the straw walker, the straw is fed into the fourth sector of the left and the third sector of the right rotation of the working bodies. The straw ejection area is shown in Fig. 4 by the unshaded part of the indicated sectors. The straw ejection area is located along the horizontal line connecting the axes of rotation of the working bodies in sectors 4 and 3. Considering that the ejection is perpendicular to the surface of the working body, it is easy to see from Fig. 4 that the most of the chopped straw will be thrown backwards away from the combine, and only a small part – to the left and right of the combine. Moreover, the ejection backwards is made by the entire blade of the radius of the working body, and to the left and right – only by its initial part. The ejection speed is directly proportional to the radius value. The ejection to the left and right is carried out at a significantly lower speed than backwards. This explains the small spreading width of the RPO-1 spreader (4–6 m). In our opinion, the straw ejection zone should be shifted to the periphery of the radii of rotation in the indicated sectors. This will increase the spread width of the chopped straw.

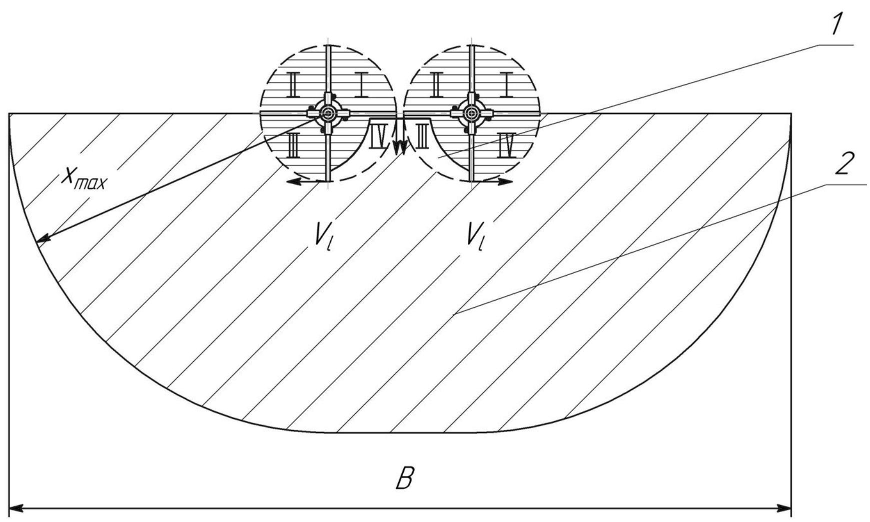
Influence of the Area and Spread Parameters on the Width and Uneven Spread of Straw and Its Chopping Length

Laboratory and field studies have shown that when optimizing the area and parameters of the straw ejection, the quality indicators of the technological process of spreading chopped straw are significantly improved (Tab. IV).

The analysis of variance showed that the following factors significantly affect the width of the chopped straw spread at the 5% significance level: the straw feeding area (factor A), the initial angle of the trajectory to the horizon (factor C), the initial spread speed (factor B), and the interactions BC, AB, AC and ABC. At the 5% significance level, the chopped straw spread unevenness is influenced by factors B, A, C and interaction AB. The significant impact on the length of straw chopping at the 5% significance level is exerted by the factors B and A.

Analysis of the studies leads to the following conclusions regarding the necessity to:

- feed the straw heap into the fourth sector of the left spreader along the direction of movement



5: *The zones of ejection of the chopped straw in the developed spreader and its spreading on the field*
1 – Chopped straw ejection area in the spreader
2 – Chopped straw spreading area on the field

of the combine and the third sector of the right spreader closer to the periphery of the radius;
- ensure the initial speed of chopped straw spread of about 63 m/s;
- ensure the initial angle of inclination of the chopped mass trajectory to the horizon of 15 degrees.

In accordance with these conclusions, we have developed an experimental radial straw spreader for a combine harvester, the scheme of which is presented in Fig. 5.

In the unshaded areas of sectors 4 and 1, the impact effect of the working bodies on the straw pile and its spread at an angle of 15 degrees occurs. The straw ejection speed is controlled by the revolutions of the working bodies.

Testing of the Developed Spreader for a Combine Harvester

The test results of the developed spreader in comparison with analogues are presented in Tab. V. The straw yield was 1.7 t/ha.

Tests show that with increased humidity of crushed mass from 10% to 20% the width of dispersion decreases for compared spreaders by 20–50%, the cutting length increases by 9–24%. It has been established that at 10% straw humidity the developed spreader provides an increase in the width of the scatter of ground straw in 2.0–2.5 times, a reduction in grinding length in 1.3–1.5 times compared with analogues. At the moisture content of the straw from 20% the width of the scatter of crushed straw is increased by 2.5–2.9 times, the grinding length is reduced by 1.4–1.6 times compared with analogues.

An assessment of the uneven straw distribution is presented in Tab. VI.

It has been found that, as the humidity of ground straw increases from 10% to 20%, the mean square variation of straw increases for compared devices by 52.8–84.3%, and the variability increases by 39.2–59.4%. At the same time, at 10% of straw humidity, the developed spreader provides a reduction in the

V: *Test results of the developed spreader in comparison with analogues*

Spreader	Chopped straw ejection area in the spreader	The angle of inclination of the trajectory to the horizon, deg.	Initial straw spread speed, m/s	Straw chopping length, cm	Spread width of the chopped straw, m	Loss of productivity during spread, %
RS-2M	Two full rotation circles of the working bodies	0	15	35*	4.5*	5*
		0	15	39**	3.5**	5**
RPO-1	Along the horizontal line connecting the rotational axes of the working bodies in the fourth left and third right sectors	0	20	29*	6*	5*
		0	20	36**	4**	5**
Developed	In the fourth left and third right sectors, closer to the periphery of the working bodies	15	63	23*	12*	6*
		15	75	25**	10**	7**

* – straw moisture 10%
** – straw moisture 20%

VI: *Statistical characteristics of straw variability*

Spreader	Chopped straw ejection area in the spreader	The angle of inclination of the trajectory to the horizon, deg	Initial straw spread speed, m/s	Average mass of ground straw in frame, gram	Standard deviation of straw, gram.	Uneven variation (coefficient of variation), %
RS-2M	Two full rotation circles of the working bodies	0	15	106.9*	51.3*	48.0*
		0	15	116.9**	78.4**	67.1**
RPO-1	Along the horizontal line connecting the rotational axes of the working bodies in the fourth left and third right sectors	0	20	81.3*	32.4*	39.9*
		0	20	97.6**	59.7**	61.2**
Developed	In the fourth left and third right sectors, closer to the periphery of the working bodies	15	63	40.8*	7.9*	19.4*
		15	75	46.3**	12.5**	27.0**

* – straw moisture 10%
** – straw moisture 20%

unevenness of the scatter of crushed straw in 2.1–2.5 times, and at 20% humidity – in 2.3–2.9 times, compared to analogues.

The effectiveness of the developed spreader for a combine harvester lies in the fact that when it is used, there is no need to use harrows to evenly distribute chopped straw over the field.

DISCUSSION

The conducted research has revealed that the spread width of the chopped mass is significantly influenced by three examined factors: the initial velocity of ejection of the chopped straw mass, the initial angle of inclination of the chopped mass trajectory to the horizon, and the area of ejection of the chopped mass from the spreader.

Studies (Voßhenrich, H.-H., 1999; von Hörsten, D. *et al.*, 2005; Müller, H. *et al.*, 2001) also note the dependence of the spread width of the chopped straw on its ejection speed. Moreover, studies (Korn, C., 2012) indicate the possibility of achieving a spread width of 12 m, and studies (Yagelsky, M. Yu.; Rodimtsev, S. A., 2016) – of even 14 m, by increasing the speed. This fully coincides with the results of our studies, according to which the initial emission rate has been increased to 63–75 m/s versus 15–20 m/s for nearest emissions.

In order to increase the spread width, the designs of some spreaders of the first and second constructive-technological schemes provide the possibility of changing the installation height of the passive deflector. According to the developers, this gives an increase in the spread width of up to 12.5% (Harvesting Tips used in North America and other harvesting advice, 2023). Most manufacturers offer the option of electric or hydraulic control of the deflector or active spreader (Yagelsky, M. Yu. and Rodimtsev, S. A., 2016). Adjusting the angle of inclination of the chopped mass trajectory to the horizon makes it possible to work with wide-cutting headers on slopes, to correct the unevenness of distribution and the influence of side wind. (Chop It, Distribute It And Do It Evenly 2008). Confirming these conclusions, our research shows the influence of three factors on the spread width, as well as their interaction. In addition to the two mentioned factors, the ejection area of the chopped straw also has an impact. Our studies show that in radial active shredders, the discharge zone determines the speed direction of the crushed straw. In order to obtain the maximum spread, it is important not only to increase the discharge rate, but to make this straw discharge in the direction left/right of the combine rather than forward/backward or at some angles. This is a new explanation for the possibility of increasing the width of the spread. This explanation of the possibility of increasing the spread is new. Our research significantly supplements the previously obtained results with new knowledge.

Studies (Voßhenrich, H.-H., 1999; von Hörsten, D. *et al.*, 2005) claim that a uniform distribution of the chopped straw mass over the field with a coefficient of unevenness of up to 20% can be ensured only with a working width of up to 6 m. However, studies (Kumhála, F. *et al.*, 2018) based on the analysis of the work of combines with axial and tangential threshing systems have established that the more straw mass comes out of the threshing, the worse its uniform distribution over the field. Therefore, the opposite is also true: the less straw mass comes out of the threshing, the better its uniform distribution over the field. This fully explains the results we obtained. Under the conditions of the arid region of northern Kazakhstan, it is easier to ensure a high homogeneity of straw distribution across the field with a width of up to 12 meters when straw is reduced under conditions of low grain yield.

According to the research results, the unevenness of the spread of chopped mass is influenced by (in descending order) the ejection velocity, the ejection area, the angle of inclination and the interaction of the first two factors. The values of these factors in the developed spreader significantly differ from the values of the factors in the analogues. As already indicated, we have increased the initial discharge rate of crushed straw to 63–75 m/s (15–20 m/s in the nearest analogues). In the nearest analogues straw is emitted in all directions (left/right, forward/backward), rather than left/right, as in the developed spreader. It is in this way that we explain the large variation in statistical indicators in Tab. IV.

The difference in the values of the factors involved (primarily the initial rate of straw release) also explains the shorter grinding length of the spreader developed compared to its counterparts in Tab. IV. It should be noted that currently there are contradictory opinions in the agrotechnical requirements regarding the length of chopping: some requirements provide for a length of shredding of up to 10 cm (Aniskin, V. I., 2005), others of up to 30 cm (Rybalkin, P. N. *et al.,* 2001). In our opinion, the contradictory opinions are caused by the difference, first of all, of straw yields. At low yields in the conditions of the northern region of Kazakhstan, straw decomposes by the sowing season of the next year even after combing (without shredding). Therefore, we consider the indicators of straw chopping at the level of 23–25 cm to be satisfactory.

CONCLUSION

In the arid conditions of the northern region of Kazakhstan, the spread of chopped straw over a harvester width of 9–12 m when harvesting grain is a big production problem. The chopper-spreaders used in the zonal conditions of the region are energy-intensive and significantly reduce the productivity of the combine; low-energy active radial spreaders do not provide the quality of soil mulching.

The theoretical and experimental studies carried out made it possible to establish that the main indicators of the quality of soil mulching by a straw active radial spreader (width and unevenness of straw spread, cutting length) depend on three factors: the chopping straw ejection area in the spreader, the initial spread speed and the initial angle of inclination of the trajectory to the horizon.

The parameters of the straw spreader are justified:

- straw ejection area in the spreader in the fourth sector of the left along the direction of movement of the combine and the third sector of the right spreader closer to the periphery of the radius;
- initial speed of chopped straw spread – not less than 63 m/s;
- the initial angle of inclination of the trajectory to the horizon – 15 degrees.

Based on the results obtained, a low-energy active radial straw spreader was developed and tested. It was found that with a straw moisture of 10–20%, the developed spreader provides a spread width of 12–10 m (in analogues 6.0–3.5 m), respectively, a spread unevenness of 27–19% (in analogues 67–40%), and a chopping length of 25–23 cm (in analogues 39–29 cm).

The effectiveness of the developed spreader for a combine harvester lies in the fact that when it is used, there is no need to use harrows to evenly distribute chopped straw over the field.

Conflict of Interest

The authors declare that there is no conflict of interest requiring disclosure in this article.

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