OPTIMIZATION OF PICKUP PARAMETERS FOR FLAX RETTED STRAW FORMATION
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ОПТИМІЗАЦІЯ ПАРАМЕТРІВ ПІДБИРАЧА ДЛЯ ПРИГОТУВАННЯ ТРЕСТИ З ЛЬОНУ

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ABSTRACT
Climatic characteristics, particularly temperature and ambient humidity, significantly affect the qualitative and quantitative indicators of flax production and fibre formation. Conventional technologies for obtaining flax fibre are based on natural dew retting, the efficiency of which depends on atmospheric moisture. The decrease in air humidity during summer periods due to climate change complicates the biological processes involved in the transformation of flax stems into retted straw. A separate harvesting technology involving low cutting of stems and their placement into windrows has been proposed to utilize productive soil moisture during retting and to accelerate seed harvesting. During field laying, windrows change their geometric parameters, become denser, and increase adhesion both between stems and with the soil surface, which requires periodic lifting and loosening. This paper presents the results of field experimental studies conducted using a developed experimental picker to determine rational structural and technological parameters based on a four-factor experimental design. Changes in windrow geometry and their interaction with the working elements of the picker were analysed. Optimal parameters of the picker for flax retting preparation were established. The study is aimed at developing a new technical solution for flax harvesting.

РЕЗЮМЕ
Кліматичні характеристики, зокрема температура та вологість навколишнього середовища, суттєво впливають на формування якісних і кількісних показників льонової продукції та процес отримання волокна. Відомі технології приготування льоноволокна ґрунтуються на природному росяному мочінні, ефективність якого залежить від рівня атмосферної вологості. Зниження вологості повітря в літній період, спричинене змінами клімату, ускладнює перебіг біологічних процесів перетворення стебел льону у тресту. Запропонована роздільна технологія збирання льону з низьким скошуванням стебел та укладанням їх у валки забезпечує використання ґрунтової вологи під час приготування трести та прискорює збирання насіннєвої частини врожаю. У процесі вилежування валки змінюють свої геометричні параметри, ущільнюються та збільшують сили зчеплення між стеблами і з поверхнею поля, що потребує їх періодичного піднімання та розпушення. У роботі наведено результати експериментальних польових досліджень, виконаних на розробленому підбирачі, з визначення раціональних конструктивно-технологічних параметрів на основі чотирьохфакторного експерименту. Проаналізовано зміну геометрії валків і їх взаємодію з робочими органами підбирача. Визначено оптимальні параметри підбирача для підготовки трести зі стебел льону. Дослідження спрямоване на розроблення нового технічного рішення для збирання льону.

INTRODUCTION
Scientific forecasts indicate that an increase in the average annual temperature by only 1°C may lead to a reduction of up to 10% in the production of certain agricultural crops, particularly cereals *(Kucher, 2017)*. The expected rise in average annual temperature by 1–3°C in the near future will significantly affect the suitability of specific regions for cultivating particular crops. Based on meteorological observations from 1945 to 2018, researchers have established that climate change has considerably improved thermal conditions in the Western Forest-Steppe and Western Polissia regions of Ukraine. At the same time, reserves of productive soil moisture have decreased.

Under these conditions, the revival of flax production in the Northern Polissia region becomes promising. Flax is considered a drought-tolerant crop due to its taproot system, which penetrates the soil to depths of up to 1 m *(Limont and Limont, 2022)*. In this region, large areas were historically allocated exclusively to fibre flax cultivation for long fibre production. Due to various economic and technological factors, flax fibre production in Ukraine has practically ceased. However, laboratory and field studies indicate that current climate changes create favourable conditions for cultivating oilseed flax. In addition to high seed yields, oilseed flax stems contain up to 25% short, non-oriented fibre. Therefore, the economic efficiency of oilseed flax cultivation can be increased through the integrated use of both seed and stem biomass *(Bauer et al., 2015; Heller et al., 2015; Makovey, 2023)*.

Modern studies confirm the relevance of improving flax harvesting technologies, including two-phase and windrow-based methods aimed at preserving fibre quality and reducing losses *(Mańkowski et al., 2017)*.

High-quality flax fibre is obtained under favourable conditions for the development of pectinolytic bacteria during the transformation of flax straw stems into retted straw. Such conditions include sufficient productive moisture and optimal temperature during field laying.

Studies on dew retting of fibre flax under the conditions of Northern Polissia, conducted by A.S. Limont, have shown that temperature is a key factor in the retting process. At the same time, the development of microorganisms and fungi also depends on moisture content and the density of the ribbon formed by stems arranged parallel to the direction of movement. Research by V. Makovey, devoted to the influence of cultivation and harvesting machinery on fibre flax quality, confirmed a correlation between long fibre yield and the characteristics of stem spreading in the ribbon. Other studies have examined the influence of tillage systems and organic cultivation practices on flax productivity *(Bilalis et al., 2010).*

The harvesting of oilseed flax for fibre is complicated by the biological characteristics of the stems, which branch from the base during crop formation and interlock at the top, making direct combining difficult *(Albota et al., 2022; Dumych, n.d.; Yaheliuk et al., 2020)*. The analysis of oilseed flax harvesting methods presented by Chuvar and Voytovich (2012) indicates the feasibility of using a separate harvesting technology under the conditions of Northern Polissia. According to this technology, oilseed flax stems at the early or early-yellow maturity stage are cut at a specified height and laid into windrows.

Further transformation of stems into retted straw under favourable conditions makes it possible to obtain fibre suitable for industrial applications *(Rennebaum et al., 2002).* Studies on the retting of oilseed flax stems in windrows have demonstrated the possibility of obtaining up to 25% short, non-oriented fibre suitable for various functional products *(Debnath, 2020; Didukh et al., 2022; Putinseva et al., 2021; Shaikh et al., 1992)*. However, the results also indicate the difficulty of obtaining fibre under conditions of insufficient atmospheric humidity.

This issue can be mitigated by utilizing productive soil moisture. For this purpose, it is proposed to cut stems at a height of 30–50 mm using rotary cutting devices that place stems into windrows parallel to the direction of machine movement. The transformation of stems into retted straw in windrows requires periodic reduction of their density due to settling and prevention of adhesion of the windrow to the soil surface and surrounding vegetation.

Among the numerous types of pick-up devices used for collecting windrows of stem crops oriented parallel to the direction of movement, belt-type pickers are widely used. These include pickers manufactured by Claas, John Deere, Schwadaufnehmer (pickup headers), Sunfloro PP-3.4 and others. However, studies or practical applications of such pickers for collecting flax windrows during retting have not been reported.

Considering the above, a new experimental picker was designed and developed for mechanizing the preparation of oilseed flax stems for retting. The machine consists of two main units: a picking mechanism and a windrow density reduction mechanism. The objective of this study is to determine the influence of the structural and operational parameters of the picker on the quality of windrow picking during the transformation of flax stems into retted straw.

MATERIALS AND METHODS

Experimental studies of the picker for the transformation of flax stems into retted straw were carried out during the 2024 growing season at the experimental field of Lutsk National Technical University (50.726433, 25.297735). Four flax cultivars were grown at the experimental site: two fibre flax cultivars (*Miandr* and *Oberig*) and two oilseed flax cultivars (*Antant* and *Lirina*). All cultivars are recommended for cultivation in the Northern

Polissia zone by the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences of Ukraine.

Sowing was performed on April 11, 2024, with a seeding rate of 35–40 kg/ha (4–5 million seeds per hectare). At the time of harvesting, the stem height of the cultivars was as follows:

- *Lirina*: 550–580 mm,
- *Miandr*: 770–920 mm,
- *Antant*: 660–800 mm,
- *Oberig*: 770–830 mm.

The stem diameter in the basal zone (cutting zone) for all cultivars ranged from 1.5 to 2.0 mm, while the relative stem moisture content was 55 ± 2%. Dimensional parameters of the crop stand, individual stems, and windrows were measured using standard measuring instruments (measuring tape, rulers, electronic calliper, and electronic angle gauge).

Stem moisture content was determined under laboratory conditions using the direct oven-drying method at a temperature of 105 °C until constant mass was achieved, as the most accurate method. For this purpose, on the day of stem cutting and windrow picking, ten stems were collected at three points along the length of the field run, placed in polyethylene bags, and immediately transported to the laboratory equipped with drying facilities. From each set of ten stems, samples weighing 5–6 g were cut in five replicates, placed in drying containers, and dried to constant mass. Additionally, prior to cutting, a separate experiment was conducted to monitor mass loss in order to construct drying curves for each flax cultivar and to determine the average moisture release rate of flax stems.

Stem cutting and windrow formation were performed using a rotary mower with a working width of 1650 mm. As a result of cutting, a windrow composed of flax stems interconnected by their tops was formed. In cross-section, the windrow can be represented by the scheme shown in Fig. 1a. Branching of oilseed flax stems from the base leads to an increase in windrow height and porosity, which facilitates the penetration of moisture and heat into the stems. Long-term observations indicate that the geometric dimensions of windrows correlate with the yield level of a given year. However, the settling behaviour of windrows during the transformation of flax stems into retted straw is similar across conditions and corresponds to the scheme shown in Fig. 1b.

Accordingly, to create favourable conditions for the development of pectinolytic bacteria during the retting of flax straw, it is necessary to reduce windrow density. The optimal condition of the window after loosening is illustrated in Fig. 1c.

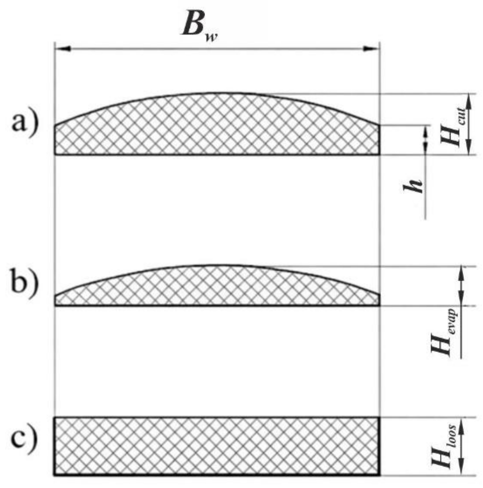


Fig. 1 – Change in the windrow cross-sectional shape during retting:
***a** – freshly formed windrow; **b** – after 8–10 days of field retting; **c** – after treatment with the picker.*

In the year of the study, the prevailing climatic conditions were not favourable for high stem biomass yield of flax, as indicated by the average stem diameter of 1.5-2.0 mm. Therefore, at a cutting height of 30-50 mm, the initial maximum height of the formed windrows ranged from 54 to 98 mm, with the deviation of cut stems from the central axis of the windrow within 8-17°. The average windrow width was approximately 1000mm.

After 10 days of field retting, a significant settling of the windrows was observed (Fig. 2), accompanied by the emergence of other plants growing through them. As a result, the windrow height decreased by approximately two times, reaching values of 25-60 mm.

Fig. 2 – Windrows of flax stems after 10 days of field retting:
***1** – Lirina; **2** – Miandr; **3** – Oberig; **4** – Antant.*

The investigated experimental picker for flax retting preparation (Fig. 3) consists of a frame (1) with a tractor-mounted hitch, which rests on two supporting drive wheels (4) and additional support wheels (12). The frame carries the picking unit (2) and the windrow density reduction unit (3).

The picking unit includes a drive drum (7) and a tension (driven) drum (8), between which a flexible belt (9) is stretched. Removable metal bars (10) with teeth (11) welded at an angle of 30° are rigidly fixed to the belt. The flexible belt (9) is driven from the supporting drive wheels (4) via a chain transmission (6). The picked windrow is loosened by three beaters (5) mounted on the windrow density reduction unit (3).

Fig. 3 – General view of the experimental picker for the transformation of flax stems into retted straw

The experimental picker is designed for picking a single windrow with a width of up to 1000 mm. To minimize stem losses and ensure the continuity of the windrow during the picking process, preliminary studies were conducted to determine the key structural and operational parameters and to adjust the picker prior to the main experimental investigations (Fig. 4).

a b

Fig. 4 – Configuration of the picking mechanism (a) and adjustment of the picker (b):
***1** – toothed bars; **2** – unpicked stems.*

Among the established parameters, the productivity of the machine–tractor aggregate depends on its travelling speed V_a, m/s. However, in the present study, the primary objective was to ensure high picking quality and effective reduction of windrow density, which depend on the travelling speed of the flexible belt (9). This speed is synchronized with the travelling speed of the aggregate via the supporting drive wheels (4) of the picker.

The inclination angle of the picker belt α, degrees, was adjusted by changing the position of the support wheels (12) relative to the frame (1). During the experiments, the distance l, mm, between the removable bars (10) was varied. At the same time, different numbers of teeth (11), pcs, were installed on the bars (10).

As a result of manufacturing the experimental picker, the following technical characteristics were established:

- Picker type – semi-mounted;
- Number of windrows picked – one;
- Minimum windrow picking height – 30–50 mm;
- Overall dimensions (without hitch), mm:
  - length – 2640;
  - width – 1250;
  - height – 750;
- Tractor traction class – 0.6.

Variation of the above parameters makes it possible to evaluate the quality of windrow picking with regard to the factors listed in Table 1.

Table 1

Values of Factors Investigated in the Experiment

Variation Levels	Factors			
	Travelling speed of the aggregate V_a (m/s)	Inclination angle of the picker belt α (°)	Distance between bars l_{pl} (mm)	Number of teeth per bar n_z (pcs)
Upper (+1)	1,15	45	400	8
Basic (0)	0,90	30	225	5
Lower (-1)	0,65	15	50	2

The quality of windrow picking was evaluated using the coefficient of picking completeness k_{pc}, which was defined as the ratio of the mass of stems picked up after the passage of the aggregate to the total mass of the windrow, expressed as a percentage.

The windrow mass along the working pass M_W was determined based on the average mass per running meter of the windrow m_{rm}. The number of measurements n along the length of the working pass was five. The mass of the picked stems M_{ps} after the passage of the aggregate was determined as the difference between the mass per running meter of the windrow m_{rm} and the mass of stems not captured by the picking mechanism within its working zone (Fig. 4b).

For this purpose, the aggregate was stopped at five pre-selected locations along the working pass. The stems that were not picked up were manually collected and weighed. Subsequently, the position of the picker elements was adjusted according to the experimental design matrix (Table 2), and the movement of the aggregate was continued. The average value of five repetitions was taken as the mass of stems not captured by the picking mechanism for the corresponding flax variety. The number of experiments for each flax variety was three, which corresponded to three passes of the picker during the 26-day period of flax stem transformation into retted straw.

To obtain a mathematical model describing the influence of the investigated factors on the quality of windrow picking in the form of a regression equation, a four-factor experimental design was applied. The study employed a symmetric, non-compositional second-order Box–Behnken experimental design (*Box G.E.P., Behnken D.W., 1960*). The significance of the regression equation coefficients was evaluated using Student's t-test, while the adequacy of the model was verified using **Fisher's criterion**.

RESULTS AND DISCUSSION

As a result of the conducted studies (Table 2), data were obtained on the coefficient of windrow picking completeness of flax stems η_0, %, which depends on the travelling speed of the machine–tractor aggregate V_a, m·s⁻¹, the inclination angle of the picker belt α, degrees, the distance between adjacent toothed bars l_{pl}, mm, and the number of teeth on one bar n_z, pcs.

Table 2

Box-Behnken design scheme and the density of the η_0 response values

Run	V_a, m/s	α, °	l_{pl}, mm	n_z, pcs	η_0, %
1	0.65	15	225	5	11.654
2	0.65	45	225	5	16.028
3	1.15	15	225	5	11.654
4	1.15	45	225	5	16.028
5	0.65	30	50	5	6.238
6	0.65	30	400	5	19.454
7	1.15	30	50	5	6.238
8	1.15	30	400	5	19.454
9	0.65	30	225	2	17.631
10	0.65	30	225	8	9.815
11	1.15	30	225	2	17.631
12	1.15	30	225	8	9.815
13	0.90	15	50	5	4.812
14	0.90	15	400	5	18.028
15	0.90	45	50	5	9.185
16	0.90	45	400	5	22.401
17	0.90	15	225	2	15.329
18	0.90	15	225	8	9.264
19	0.90	45	225	2	21.452
20	0.90	45	225	8	11.887
21	0.90	30	50	2	10.788
22	0.90	30	50	8	2.972
23	0.90	30	400	2	24.004
24	0.90	30	400	8	16.188
25	0.90	30	225	5	12.367
26	0.90	30	225	5	12.367
27	0.90	30	225	5	12.367

The experimental studies were carried out according to a four-factor Box–Behnken experimental design, which made it possible to obtain a mathematical model describing the dependence of the coefficient of windrow picking completeness of flax stems on the main design and technological parameters of the picker mechanism. The experimental data were processed in the Mathcad environment using second-order regression analysis. The calculated value of the Fisher criterion $F^{calc} = 2.655$ was determined based on the variance of inadequacy $S_{n.}^2 = 0.18$ and the variance of experimental reproducibility $S_y^2 = 0{,}068$.

The tabulated value of the Fisher criterion at a significance level of 5% was determined as follows:

$$F^{tab}(0.05; f_2; f_1) = 19.43, \quad (1)$$

where: $f_2 = 18$ is the degrees of freedom for the lack-of-fit variance, and $f_1 = 2$ is the degrees of freedom for the experimental reproducibility variance.

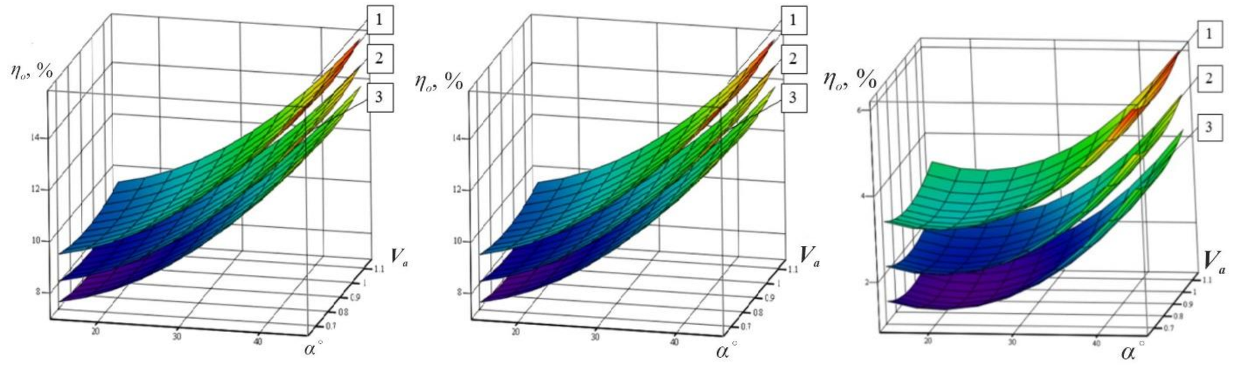
Since:

$$F^{calc.} = 2.655 < F^{tab}(0.05; f_2; f_1) = 19.43, \quad (2)$$

the regression model was found to be adequate at the 5% significance level.

After transforming the factors into their natural values, the regression equation (3) was obtained, based on which the response surface was constructed (Fig.5).

$$\eta_0 = 15.167203 + 0.004965 \cdot \alpha^2 - 0.019444 \cdot \alpha \cdot n_z - 0.054911 \cdot \alpha + 0.000004 \cdot l_{pl}^2 + \\ +0.03596 \cdot l_{pl} + 0.111 \cdot n_z{}^2 - 1.82933 \cdot n_z + 5.712 \cdot V_a^2 - 10.2816 \cdot V_a \quad (3)$$



a) b) c)

Fig. 5 – The response surfaces were constructed based on the regression equation (3)

a) n_z = 2; b) n_z=5; c) n_z = 8

The analysis of the influence of the investigated factors on the operating efficiency of the picker mechanism shows that, within the studied range, the travel speed of the machine–tractor aggregate (MTA) has an insignificant effect on the quality of windrow picking, due to the synchronization of the working elements of the picker mechanism with the aggregate motion. The distance between adjacent tooth bars should be selected taking into account the length of flax stems. An increase in the number of teeth on a single bar improves the quality of windrow picking; however, insufficient spacing between the teeth complicates the release of the stems.

The quality of picking decreases sharply with an increase in the inclination angle of the moving belt to the value of α = 45°. Therefore, when using the picker mechanism in combination with other agricultural machines, it is important to consider the optimal inclination angle, the rational value of which is α = 30°.

Based on the obtained values of flax stem losses during windrow picking throughout the period of flax stem transformation into retted straw during the factorial experiment, the average value of the windrow picking completeness coefficient η_0(Table 3) was determined for each of the studied flax cultivars. These values and their confidence intervals were calculated using the Mathcad computer mathematics system.

Table 3

Average values of windrow mass and windrow pickup completeness coefficient

Variety	Average mass per running meter of windrow, m_p, kg	Windrow mass along the run length, M_v, kg	Pickup date: 22.07.24 m_p, kg	22.07.24 M_v, kg	Pickup date: 02.08.24 m_p, kg	02.08.24 M_v, kg	Pickup date: 12.08.24 m_p, kg	12.08.24 M_v, kg	Average pickup completeness coefficient η_0
Liryna	0.48	48	0.50	50	0.47	47	0.46	46	0.88
Miandr	0.72	72	0.75	75	0.71	71	0.70	70	0.93
Antant	0.58	58	0.60	60	0.57	57	0.56	56	0.91
Oberih	0.76	76	0.78	78	0.75	75	0.74	74	0.94

Thus, the average value of the windrow pickup completeness coefficient η_0 varies within the range of 0.88–0.94, which indicates a functionally reliable design of the pickup mechanism. These values, to a certain extent, correlate with the stem length of the studied flax varieties and their botanical type, which determines the cohesiveness of the windrow. An increase in the pickup completeness coefficient η_0 can be expected under conditions of higher stem biomass yield.

The cultivation of oilseed flax variety Lirina and fibre flax variety Miandr on the same field in 2023 under more favourable agro-climatic conditions resulted in a significantly higher stem yield. During that season, the stem height of the Lirina variety ranged from 780 to 850 mm, while for Miandr it ranged from 980 to 1150 mm, with stem diameters in the basal zone of 3.5–4.0 mm. Under these conditions, the thickness of the windrows formed by the cut stems ranged from 188 to 203 mm. Tensile strength tests of such windrows showed significantly higher values compared to the windrows formed in 2024, which is a positive factor for the operation of the proposed pickup mechanism.

Accordingly, during the experimental periods of windrow pickup, the moisture content of the stems was determined. Based on the obtained average values, a drying curve was constructed, which revealed an increase in stem moisture at points A_1 and B_1 as a result of the formation of productive moisture within the windrow (Fig. 6).

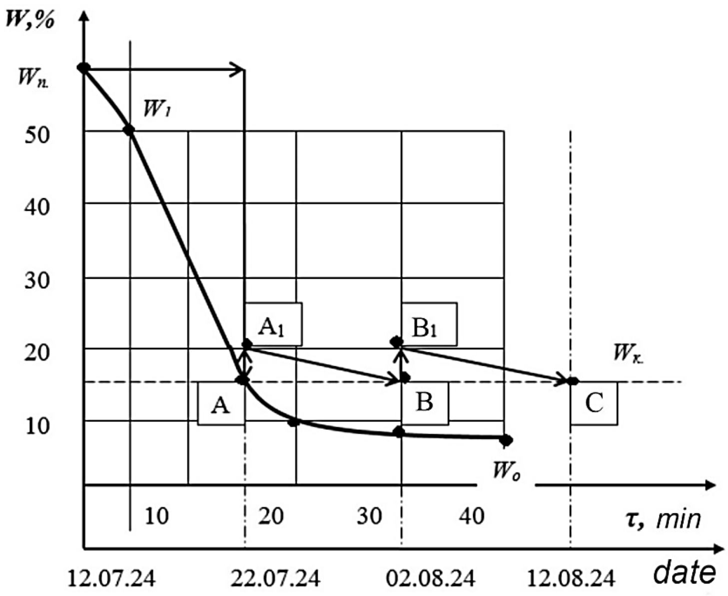


Fig. 6 – Averaged drying curve of flax stems (2024 harvest) with superimposed values of productive moisture within the windrow

Analysis of the drying curve indicates that the moisture content of flax stems at the time of cutting was approximately 55%. After cutting and forming the windrow, the stems intensively release moisture into the surrounding environment (points A and B), as evidenced by the linear section of the curve. In the absence of external mechanical disturbance, the dehydration process slows down due to the uneven influence of ambient temperature on the stems within the windrow, which gradually settles. The lower layers of the windrow remain moister than the upper layers, resulting in an increase in the average stem moisture content (point A_1) by approximately 3–5%. A similar increase is observed during each lifting of the windrow (point B_1). Consequently, a uniform redistribution of productive moisture across the windrow height accelerates the process of flax stem transformation into retted straw (retting).

CONCLUSIONS

- As a result of field experimental studies of the experimental pickup, a mathematical model in the form of a regression equation was obtained for the first time. The model describes the influence of design and technological parameters of the pickup mechanism on the coefficient of windrow pickup completeness of flax stems oriented parallel to the direction of movement of the machine–tractor unit. The adequacy of the model was confirmed using the Fisher criterion at a significance level of 5%.

- It was established that within the investigated range of values, the travelling speed of the machine–tractor unit has an insignificant effect on the quality of windrow pickup. This is explained by the synchronization of the flexible belt speed of the pickup mechanism with the forward speed of the unit through the supporting drive wheels.
- It was proven that the inclination angle of the moving belt of the pickup mechanism is one of the determining factors influencing the efficiency of the pickup process. An increase in the inclination angle to $\alpha = 45°$ leads to a sharp decrease in the pickup completeness coefficient. A rational inclination angle ensuring stable operation of the pickup mechanism is $\alpha = 30°$.
- It was determined that the distance between adjacent toothed bars should be selected with regard to the length and cohesion of flax stems within the windrow. An improper choice of this parameter results in increased stem losses and disruption of windrow continuity during pickup.
- An increase in the number of teeth on a single bar leads to a higher pickup completeness coefficient. At the same time, an excessive number of teeth reduces the inter-tooth spacing, which complicates stem release and may negatively affect the stability of the technological process.
- Based on the results of multi-day field trials, it was established that the average value of the windrow pickup completeness coefficient for the investigated flax varieties ranges from 0.88 to 0.94, indicating the operational capability and technological feasibility of the proposed pickup mechanism design.
- It was shown that periodic lifting and loosening of windrows during the transformation of flax stems into retted straw promotes uniform redistribution of productive moisture over the windrow height. This creates favourable conditions for the activation of pectin-degrading microorganisms and accelerates the retting process.
- The obtained results can be used in the design and adjustment of pickups for separate flax harvesting technologies, as well as in the improvement of retting preparation processes under conditions of atmospheric moisture deficiency.

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