MACHINE FOR SPRING TECHNOLOGICAL HARVESTING OF INDUSTRIAL HEMP / *МАШИНА ДЛЯ ТЕХНОЛОГІЧНОГО ВЕСНЯНОГО ЗБИРАННЯ ТЕХНІЧНИХ КОНОПЕЛЬ*

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ABSTRACT
The development of industrial hemp production necessitates the creation of new technical means and methods, and the refinement of technological approaches for cultivating and harvesting this crop. The harvesting process requires special attention, which is determined by the characteristics of this crop, the stems of which contain strong fibers making it difficult to cut them. The article discusses the efficiency of using the machine that was developed and manufactured for spring harvesting of hemp stalks. The parameters of the hemp stalks windrow were considered, taking into account the factors affecting its quality. In addition, there were selected the parameters to asses the quality of the resulting windrow. The research was carried out using probability theory and statistical methods. Through experimental studies, the functionality of the developed and manufactured machine was confirmed. It was established that the machine facilitates the formation of a uniform windrow from hemp stalks, with the skew cutting angle not exceeding 17˚, which allows it to be collected with a baler, minimizing the risk of clogging.

РЕЗЮМЕ
Розвиток промислового коноплярства зумовлює необхідність створення нових технічних засобів і методів, а також удосконалення технологічних підходів до вирощування та збирання цієї культури. В Україні, де коноплярство переживає період активного зростання, існує особлива потреба в технічних рішеннях, здатних забезпечити якісний процес збирання врожаю і при цьому залишатися доступними для відносно невеликих господарств.
У статті розглядається ефективність розробленої та виготовленої машини для весняного збирання стебел конопель. Розглянуто параметри валка стебел конопель з урахуванням факторів, що впливають на його якість. Крім того, були обрані параметри для оцінки якості отриманого валка. Дослідження проводилися з використанням теорії ймовірностей та статистичних методів. За допомогою експериментальних досліджень підтверджено працездатність розробленої та виготовленої машини. Встановлено, що машина сприяє формуванню рівномірного валка зі стебел конопель, при цьому кут нахилу зрізу не перевищує 17˚, що дозволяє збирати його прес-підбирачем, мінімізуючи ризик засмічення.

INTRODUCTION
Hemp is a crop that garners widespread interest among scientists, farmers and industrial producers due to its versatile applications. Currently, bast fibers are utilized for industrial applications in the textile, construction, automotive, and other industries both in Europe and China (*Nalobina et al, 2017; Popa et al, 2022*). Recently, bast fibers have also gained importance as a renewable raw material for the production of strong, lightweight composite *(Pari et al., 2015)*.

Considering the potential of hemp cultivation and its diverse applications, Ukraine is experiencing a resurgence in this industry. This revival necessitates the adoption of innovative technologies for cultivation, harvesting and primary processing aimed at enhancing the product quality and reducing losses.

The increase in hemp cultivation in Ukraine underscores the need for widespread mechanization, particularly in hemp harvesting, which is the most labor-intensive phase of cultivation.

Hemp has become the focus of research for numerous scientists, covering a wide range of directions. These include investigations into the physical and mechanical properties of stalks and fibers *(Moskalenko and Giliazetdinov, 2011; Xiaoping et al, 2013; Wu et al, 2010; Sankari, 2000).*

Specifically, the research has revealed variations of hemp stem fiber across the different parts of the hemp stem. The mechanical properties (modulus of elasticity and hardness) of the fiber cell wall in the lower section were found to differ from the upper sections of the hemp stem *(Hrydiakin, 2015).* Hemp harvesting technologies are somewhat different from those used for harvesting other agricultural crops, and they require the use of specialized equipment capable of performing several technological operations in one pass. In addition, the process is complicated by the plant height at the time of harvesting, as well as the structure of the stems, which contain a strong fibrous layer and wood component. Therefore, an urgent issue in the hemp industry is the intensification of harvesting operations, the use of modern harvesting technologies and technical means to increase the level of mechanization in the industry.

The research by *Zaica et al, (2022)*; *Popa et al., (2022)*; *Assirelli et al., (2020); Sadrmanesh and Chen (2019); Huang et al., (2023); Huang, Shen, Li, (2017); Pari, Alfano, Scarfone., (2016); Huang, Shen, Ji , Tian et al., (2020); Zhu, Zhang, Yu.,(2018); Li , Shu, (2010); Burczyk., Kaniewski , (2003); Bulgakov et al., (2015),* and others are dedicated to solving this issue.

Burczyk and Kaniewski, (2008) proposed a method of harvesting hemp seeds and a device for its implementation, which provides mowing and cutting the stems into smaller parts, allowing effective use for the production of essential oils. This method is recommended for use during the hemp flowering phase. This device can be also used during the period of complete ripening of seeds in order to harvest them for further preparation of seed material.

The process of harvesting hemp seeds has also become the subject of scientific research by *Baraniecki et al, (2022)*, who investigated the operation of a B-800 mower, which was attached to a John Deere 6830 tractor with the power of 104.4 kW. The performance of this mower in hilly terrain was evaluated during hemp harvesting. The authors recommend to use this equipment in relatively small farms, which are usually unable to purchase expensive and bulky machinery for hemp harvesting.

The studies by *Păun A. et al, (2020); Manea D. et al, (2023),* who also investigated hemp harvesting equipment, contain the results obtained as part of the research project conducted by INMA Bucharest. The presented equipment was tested on the experimental site. The kinematic and power parameters were obtained, and their influence on the quality indicators of the harvesting process, in particular the cutting height of the stems, was investigated. The conducted research allowed the authors to provide certain recommendations on the harvesting process efficiency.

The research of *Bulgakov (2015); Huang (2023); Huang, Shen, Li (2017); Huang, Shen, Ji, Tian et al. (2020); Pari, Alfano, Scarfone (2016)* were devoted to the development and analysis of the hemp harvester performance. Combine harvesters are able to ensure harvesting in large and level fields. In addition, these are rather complex and bulky machines that are not suitable for use in small farm fields. A significant deterrent to the use of combines by small and medium-sized farmers is their high price. Therefore, some researchers *(Zhu et al., 2018; Li et al, 2010)* suggest using well-known headers. The authors found that the reapers were not effective due to frequent baler clogging, uneven stem cutting and breakage of cutting elements.

The analysis of the latest research helped conclude that the issue of efficiently organizing hemp harvesting operations is relevant, while the issues of harvesting technologies that would ensure obtaining high-quality products, both seeds and fiber, are not sufficiently studied. In addition, the machines produced by well-known machine-building companies are bulky and energy-consuming. Considering this, the research focused on developing the equipment and technologies for small farms, which will facilitate the development of the hemp industry, is highly relevant. Therefore, this study aims to develop a compact device for the spring harvesting of hemp stalks suitable for small farms and to evaluate its operational effectiveness.

MATERIALS AND METHODS

Hemp harvesting employs various technologies, including the one developed and introduced by he Institute of Bast Crops of the National Academy of Sciences of Ukraine which is known as spring hemp harvesting. According to this technology, crop harvesting is carried out in two stages. Initially, seeds are harvested using a combine harvester in autumn, followed by stalks harvesting in spring after rotting of the hard stalks at the root, requiring less effort for their removal. To break the stalks during the second stage, a rotary rake is offered to be utilized. However, this process results in uneven windrows of stalks with significant relative displacements. These uneven windrows can lead to clogging of balers during the pickup. Consequently, the baler must be stopped periodically to clear the clogs, thereby increasing the harvesting time *(Nalobina et al, 2017)*.

In order to eliminate stoppages of the baler due to obtaining a uniform windrow from broken stalks in the field, a specialized machine for spring hemp harvesting was developed and manufactured (Fig. 1).

The newly manufactured machine operates as follows: the drive pulley 2 is powered by the power take-off shaft of the tractor, which in turn drives the belts equipped with firmly positioned fingers on them. During this period, following the winter season, the stalks are weakened at the root, making them prone to easy breakage. The fingers transport the stalks from left to right and place them in windrows. The machine offers two options for finger placement on the belts: sequential placement (Fig. 2) and a checkerboard pattern arrangement.

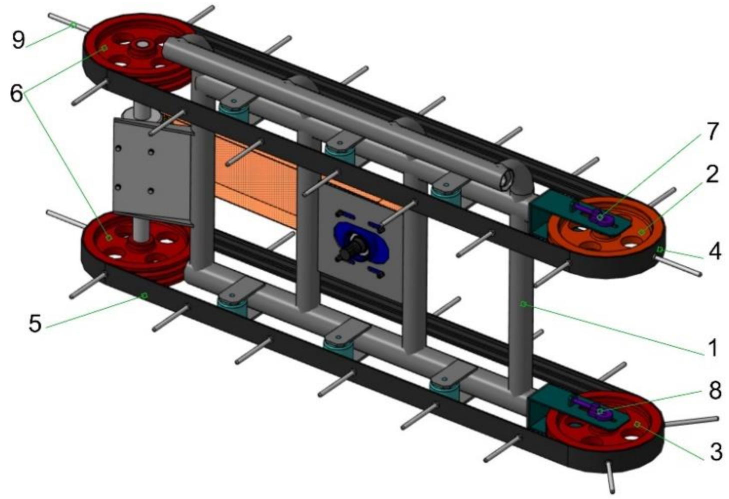

Fig. 1 - Machine for springtime hemp stalk breaking:
1- frame, 2,3- upper and lower driving pulleys, 4,5 – belts, 6-driven pulley, 7,8 – tightener, 9-finger

2-

Fig. 2 – Machine for harvesting hemp stalks

To assess the functionality of the machine, the parameters of the process of forming a hemp stalks windrow will be examined, assuming the implementation of spring harvesting technology.

Figure 3 illustrates the parameters of the stalks windrow formation.

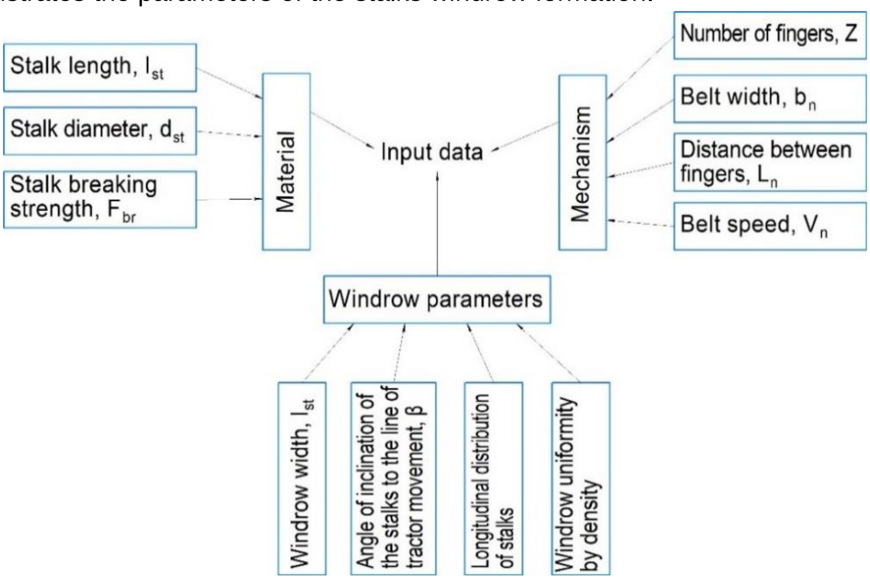

Fig. 3 - Factors influencing the windrow laying process and determining its quality

Consider the above factors.

1. Stalk length l_{st}. The given parameter depends on the variety of hemp, conditions for its cultivation. The average length of stalks (after removing the seed part) in the experimental field is 62.7 cm. The maximum length is 98.7 cm, the minimum is 57.9 cm. The diameter of stalks d_{st} = 0.85…1.97 mm. Breaking force is F_{br} = 4.72…7.55 N.

2. Machine parameters

The number of fingers on the upper and lower belts is 24 pieces. The width of the rubberized belt is 10 cm.

3. Windrow parameters

The width of the windrow l_w, laid out in the field depends on the uniformity of stalks composition conveyed from the fingers of the machine carrier, the difference in the stalks height after mowing the seed part, the uniformity of the field surface, and the speed of the machine movement.

The windrow width can be described by the following equation:

$$l_w = l_{avg} \cdot \delta \ [m] \tag{1}$$

where:

l_{avg} – average stalk length, m;

δ – windrow extent in the field,

$$\delta = 1 + \frac{\Delta l}{l_{avg}} \ [m] \tag{2}$$

where:

Δl is the value of displacement (relative to the distortion) of stalks in the windrow, which will depend on the displacement of the lower (upper) part of the stalks after they leave the fingers relative to some optional value.

In the field, the stalks are uneven in height. Taking into account the distribution of various heights, it can be observed that the tops of stalks are distributed according to the normal law (Fig.4).

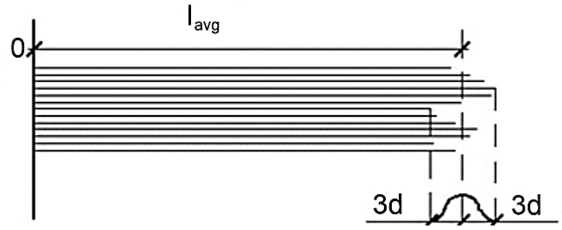

Fig. 4 - Distribution of the stalk tops

Taking into account the above, the assumption is adopted that after laying the windrow from broken hemp stalks and being moved by the machine in the field, the basal areas and tops are distributed according to the normal law. This implies that the density of the distribution of the tops $f(x_t)$ and the basal parts $f(x_b)$ will be determined as follows:

$$\begin{cases} f(\mathrm{x_t}) = \frac{1}{\sigma_t\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma_\mathrm{t}^2}\right) \\ f(\mathrm{x_b}) = \frac{1}{\sigma_\mathrm{b}\sqrt{2\pi}} \exp\left(-\frac{\left((x-l_\mathrm{avg})-\mu\right)^2}{2\sigma_\mathrm{b}^2}\right) \end{cases} \tag{3}$$

where:

μ – mathematical expectation;

σ^2 – variance of a random variable;

σ_t – mean square deviation of the basal parts and tops, respectively;

l_{avg} – the average length of stalks in the windrow.

Given that the probability of a random value (abscissa representing the position of the stalk top) falling within the expected interval is 99.7%, the system of equations (3) takes the form provided below:

$$\begin{cases} f(x_b) = \frac{1}{\sigma_\mathrm{t}\sqrt{2\pi}} \exp\left(-\frac{(x_\mathrm{t}-3\sigma_\mathrm{t})^2}{2\sigma_\mathrm{t}^2}\right) \\ f(x_\mathrm{b}) = \frac{1}{\sigma_\mathrm{b}\sqrt{2\pi}} \exp\left(-\frac{(x_\mathrm{b}-3\sigma_\mathrm{b})^2}{2\sigma_\mathrm{b}^2}\right) \end{cases} \tag{4}$$

where: $x_t = x - l_{avg}$.

It should be noted that σ_t and σ_b are determined by the unevenness of the field, the stalk length, and the machine parameters.

An important indicator for evaluating the quality of the windrow spread in the filed is the angle of inclination of stalks in the windrow. The ideal windrow configuration is achieved when the stalks in it are laid oud out parallel to each other and positioned at an angle of 90° to the direction of motion (Fig. 5).

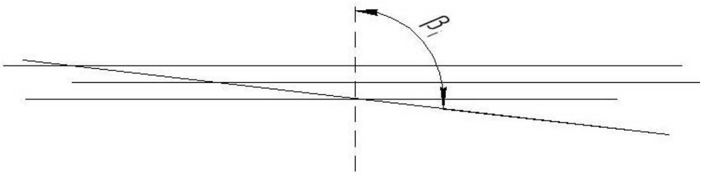

Fig. 5 - Pattern of displacement in the windrow (in relation to the direction of the machine motion)

The manifestation of the β_i value is probabilistic, thus it will be assessed using the part of the event occurrence *(Chung, 2001)*.

Relative frequency of the event occurrence is:

$$p(\beta_i) = \frac{M}{N} \quad (5)$$

where:

M is the number of trials when event β_i occured;

N is the number of all trials.

The uniformity of the windrow in terms of density is a significant indicator for evaluating the quality of the hemp harvester. The windrow spead in the filed must exhibit uniform linear density to ensure unobstructed collection by the baler without any clogging and the formation of rolls with uniform density along their height. This is important for the preservation of rolls and their subsequent processing.

The number of stalks on one linear meter of the windrow laid out in the field is determined by the formula:

$$i = B_{\mathrm{t}} \cdot i_0, \quad (6)$$

where:

B_{t} is the machine grip width, m;

i_0 is the stalk density (the number of stalks per square meter of the field), items/m^2.

The linear density, items/m^2 of stalks is determined as follows:

$$\rho = B_{\mathrm{m}} \cdot i_0 \cdot \frac{V_M}{V_{\mathrm{t}}}, \quad (7)$$

where:

B_m is the machine grip width, m;

i_0 is the stalk density (the number of stalks per square meter of the field), items/m^2.

V_m, V_b are the speeds of the machine and the belt with fingers, m/s.

RESULTS

The research was conducted in the fields of Rivne region, Ukraine. Stalks were harvested using spring technology. The newly developed and manufactured machine was used for harvesting.

The characteristics of the stalk density (average values over the two years of the research) are given in Table 1.

Table 1

Stem density parameters

No.	Parameter name	Value	Measuring units
1	Stalk maximum height	98.7	cm
2	Stalk minimum height	57.9	cm
3	Average height value (100 stalks)	64	cm
4	Average stalk diameter	1.23	cm

The windrow width was determined by measuring one hundred one-meter-long windrow sections. The relative displacement of basal parts and tops was also measured. Statistical processing of the experimental data resulted in creation of a distribution graph confirming the earlier assumption regarding the normal distribution of these values (Fig.6).

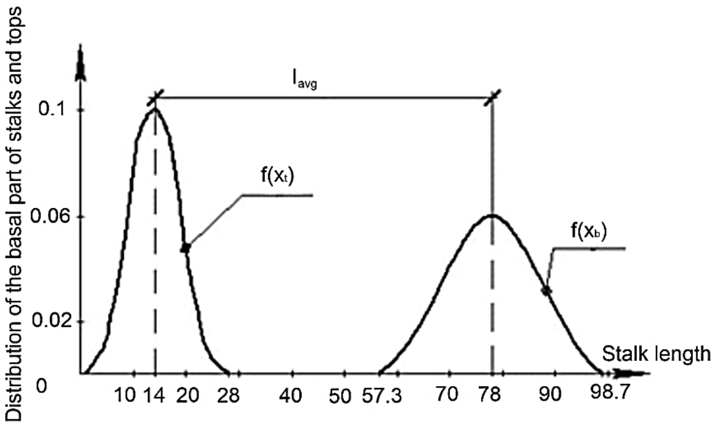

Fig. 6 - Distribution of the basal part of stalks and tops in the windrow (stalk length)

With the obtained distribution, given that l_{avg}=64 cm, the mean square deviation of the basal parts of stalks $\sigma_b = 4.6 \approx 5cm$, the mean square deviation of the tops $\sigma_t = 6.6 \approx 7cm$, no clogging is observed.

The results of the study of the skew cutting angle β_i are depicted in Fig.7.

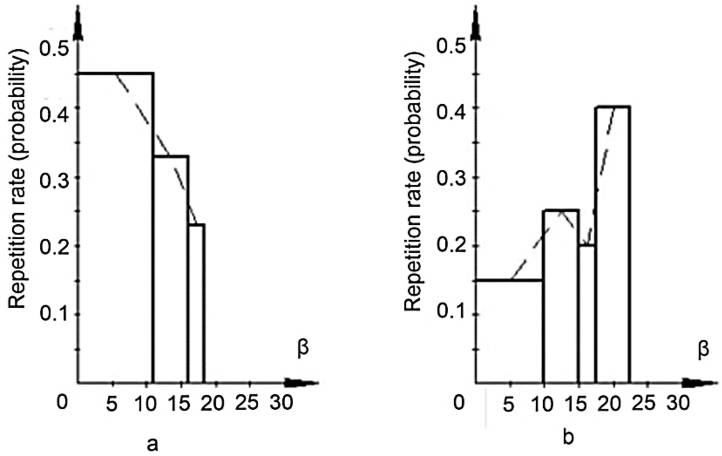

Fig. 7 - Distribution density of the probability of β_i indicator manifestation under the conditions of using the machine for harvesting hemp (mean values from one hundred one-meter-long plots):
a– PTO shaft speed is 530 rpm; b – PTO shaft speed is 1123 rpm.

It is evident that reducing the rotation speed of the machine drive pulley and, accordingly the belt speed, has led to a decrease in the number of stalks deviating from the line perpendicular to the direction of the machine movement.

In addition to the speed of the machine belt movement, changes were made to the arrangement of the fingers on the belt. Experiments were also conducted with the machine where fingers were arranged in a checkerboard pattern. The results are shown in Fig.8.

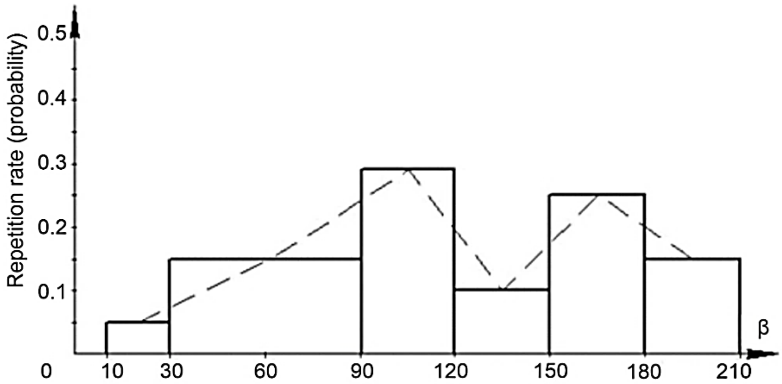

Fig.8 - Distribution density of the probability of β_i indicator manifestation under the conditions of arranging the fingers in a checkerboard pattern and the rotation speed of the PTO shaft set at 530 rpm

Due to significant stalks displacement along the windrow length, checkerboard arrangement of fingers is not efficient.

CONCLUSIONS

As a result of the field tests of the machine for hemp spring harvesting, it was determined that:

- the machine is to be manufactured with a sequential arrangement of fingers on 10 cm-wide belts with a distance between fingers of 41 cm;
- the diameter of the machine drive pulley is 250 mm with the pulley width of 100 mm;
- the tractor's PTO shaft is expected to have the rotation speed of 530 rpm.

Adherence to these conditions ensures the formation of a uniform windrow of hemp stalks in the field, enabling the baler to collect the windrow without clogging or stopping.

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