IMPROVING THE EFFICIENCY OF HARVESTING SUNFLOWER SEED CROPS
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ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ЗБИРАННЯ НАСІННЄВИХ ПОСІВІВ СОНЯШНИКУ

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ABSTRACT
The relevance of research is conditioned by the need to improve the efficiency of plot combines for harvesting sunflower seed crops. Experimental studies were carried out by planning and staging multifactorial experiments. The dependence of the force factors influence on the seed shedding from a sunflower basket was obtained based on the laboratory studies results. This dependence makes it possible to evaluate the influence of the parameters of the harvester header on the value of seed losses from shedding. The study made it possible to substantiate the design of the header attachment of the plot combine, consisting of a three-blade reel, box-type dividers and side shields. An experimental sample of the header attachment to the "Sampo-500" grain harvester has been developed and manufactured. Experimental studies of the influence of the speed of the combine movement and the coefficient of the operation kinematic mode of the reel to the developed device on the quality indicators of the harvesting of sunflower crops seeds were carried out.

АНОТАЦІЯ
Актуальність досліджень обумовлена необхідністю підвищення ефективності роботи селекційних зернозбиральних комбайнів на збиранні насіннєвих посівів соняшнику. Експериментальні дослідження проводили шляхом планування та постановки багатофакторних експериментів. За результатами лабораторних досліджень отримано залежність впливу силових чинників на осипання насіння з кошика соняшника, що дозволило оцінити вплив параметрів жниварки комбайна на значення втрат насіння від осипання. Проведене дослідження дозволило обґрунтувати конструкцію пристосування до жниварки селекційного комбайна, що складається з трилопатевого мотовила, подільників коробчастого типу та бокових щитів. Проведені експериментальні дослідження впливу швидкості руху комбайна та коефіцієнта кінематичного режиму роботи мотовила до розробленого пристосування на показники якості збирання насіннєвих посівів соняшнику.

INTRODUCTION
Sunflower crops have grown significantly in Ukraine during recent years. According to the State Statistics Committee, in 2021 the area under sunflowers reached 6.51 million hectares, which is 23.9% of the structure of sown areas of Ukraine (Table 1). Compared to 2010, the area under sunflower crops has increased by more than 40%. This necessitates an increase in seed production (*Vasylkovska et al., 2021*). The need for seed material in Ukraine is about 35 thousand tons per year.

Table 1

Dynamics of changes in the area of sunflower crops in Ukraine

Year	2010	2015	2016	2017	2018	2019	2020	2021
Crop area, million hectares	4.50	5.2	5.90	5.94	6.06	5.85	6.38	6.51

The harvesting process plays an important role when growing seed sunflower. A characteristic feature of growing most varieties of sunflower is the uneven ripening. Harvesting of sunflower seeds begins in the period when 85-90% of plants in the field reach the stage of economic maturity. The period of sunflower harvesting is limited by agrotechnical terms. Sunflower seed crops should be harvested within 5-6 days. If the collection began in the phase of full ripeness, then on the fifth day the losses from seed shedding increased by 2 times, and on the 15th day by 10-12 times. Therefore, the quality of its implementation depends on the level of technical equipment of this technological process (*Rogovskii et al., 2021*).

The use of plot combines for harvesting sunflower from seed plots leads to significant losses due to seed shedding and damage due to interaction with the working bodies of the combine. According to experts, seed losses reach 15% when mowing sunflower stems with technical means (*Vasylchuk, 2021; Startsev et al., 2020*).

An analysis of the results of scientific research shows that more seeds are lost by the headers of combine harvesters when harvesting sunflowers (*Xu et al., 2019*). Losses behind the header of a combine harvester can be more than 50% of total losses when harvesting sunflower seeds (*Zareei & Abdollahpour, 2016*). Therefore, reducing this part of the loss to the allowed value within 1.0-1.5% is an important step in reducing the loss of sunflower seeds (*Nalobina et al., 2019*).

Y. Liu et al., (2021), note that according to the results of tests on harvesting sunflower seeds, the loss on the harvester with a rigid clamping and transporting device was 5.17%. According to the results of industrial inspection at seed moisture values of 9-12%, losses on row-type harvesters were 0.9-1.6% with the level of total losses for combine harvesters in the range of 1.8-2.4% (*Chaplygin et al., 2019*).

When using combine headers, there is an accumulation and jamming of the mass of stems between the dividers and the reel, the rejection of sunflower stalks by the reel outside the harvester, which leads to increased seed loss during harvesting (*Liu et al., 2020*). Therefore, it is necessary to provide conditions of uniform, smooth giving of stalks by the reaper in a threshing machine of the combine harvester.

The combine header is a complex technical system, in which several factors are involved. This is the state of crops, including variety, seed moisture, stem slope, density and uniformity of plant placement. In addition, crop losses are affected by the speed of the combine, the performance of the reel, the height of the reel, the service life of the cutting machine. These factors should be regulated and controlled in accordance with the working conditions to prevent significant crop losses during harvesting (*Narvane &* Panwar, *1996*).

The cutting table device in the combine cannot meet the harvesting requirements of high efficiency and low damage, according to the seed damage rate and loss rate of sunflower during harvesting *(Jin et al., 2021*). It has been established that combine headers equipped with a reel lose less sunflower seeds than row-type devices when harvesting relatively small experimental and selection plots *(Shaforostov & Makarov, 2007*).

A number of shortcomings are noted when harvesting sunflower with a combine harvester equipped with a serial header with an eccentric reel. First of all, the seeds are knocked out of the baskets due to impact on them when the reel bar enters the plant mass. Also the transshipment of cut baskets through the reel bar and their fall onto the field is observed. This leads to a deterioration in the quality of harvesting (*Gutrov, 2006*).

In the work of *K.A.M. Ali et al., (2020),* it was noted that the quantity and quality of harvested seeds deteriorate significantly during harvesting. It is established that the rational values of the factors influencing the process of sunflower harvesting are: combine speed is 4.8 km/h; kinematic mode of operation of the reel is 1.25-1.5; height of installation of a reel over the cutting device is 15-25 cm. Seed moisture is an influential parameter at each stage of harvesting.

V.D. Shaforostov et al., (2018), note that the use of modern technical means for seed sunflower harvesting is associated with crop losses, which can reach 10–11%. One of the reasons is a significant range of the height of the placement of baskets above the field surface, which for breeding plots can reach 125 cm.

The research of *Mirzabe A.H. et al., (2016),* present the results of a study of the size characteristics of sunflower plants during the harvesting period. The authors note a significant uneven placement of the height of sunflower heads and the absence of a correlation between the diameter and height of the sunflower heads. At the same time, there is a clear linear relationship between the diameter of the basket and the weight of the seeds in it.

F. Shahbazi et al., (2011), conduct research of the moisture content effect on the physical and mechanical properties of sunflower stems. It is found that the bending effort and Young's modulus decrease with increasing humidity. Shear effort and specific shear energy increase with increasing water capacity.

M.A.F. Abd-El-Maksoud et al., (2009), studied the effect of combine harvester header parameters on sunflower seed losses during harvesting. It was noted that a decrease in seed moisture and an increase in the speed of a combine harvester is accompanied by an increase in losses in the header.

In the studies of *O.O. Nalobina et al., (2021),* noted that the value of losses of sunflower seeds is significantly affected by the length of the stems cut by the harvest along with the heads.

The authors proposed the design of additional rotors recommended for installation in the lower part of the header which reduces losses by 5%.

In the study *S.O. Kustov (2013),* a mathematical model of the interaction of the reel blade was developed, which makes it possible to determine the value of the impact velocity during its contact with the sunflower. Obviously, the creation of conditions for minimizing the impact speed of the blade will reduce the loss of sunflower seeds during harvesting.

Analysis of the results of the reviewed studies allows establishing the directions of the following research:

- to experimentally investigate the influence of force factors on shedding of sunflower seeds during harvesting;

- to substantiate the design and rational parameters of adaptation to the header of a combine harvester for collecting seeds of sunflower crops;

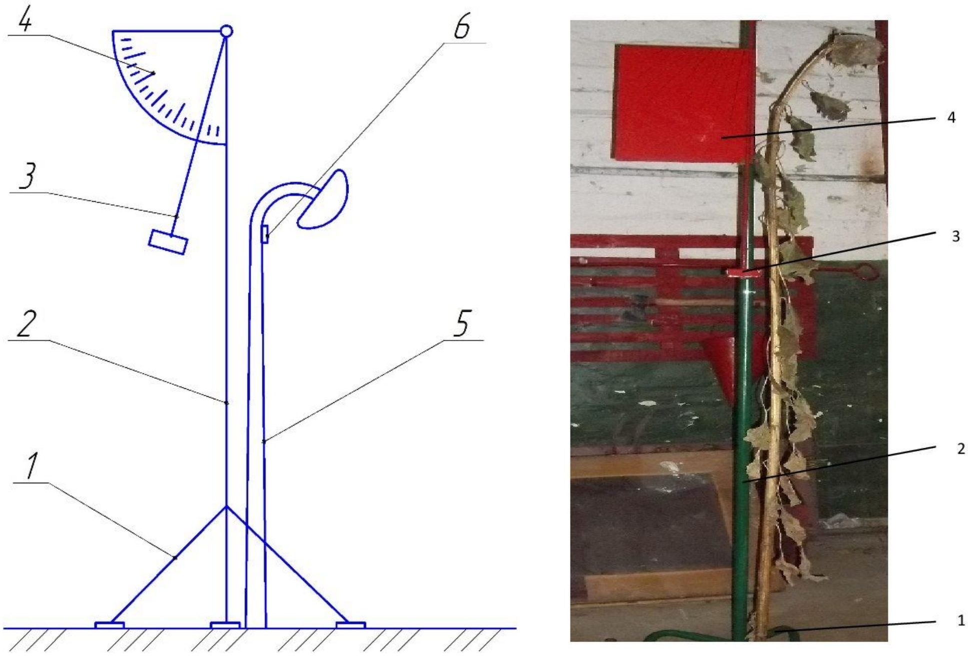
- to experimentally investigate the influence of the operating modes of the developed device on the quality indicators of the collection of sunflower seed crops.

The purpose of the research is to reduce the seed loss during the harvesting of sunflower seed crops by developing a design and rationale for the parameters of a header attachment of a plot combine.

MATERIALS AND METHODS

The study of the influence of force factors on the shedding of sunflower seeds during harvesting was carried out by planning and staging a multifactorial experiment. The purpose of laboratory studies was to establish the loss of seeds from sunflower heads in the artificial reproduction of the action of the reel. A load weighing 5 kg was retracted to a certain distance and released. Acquiring a certain speed (reel movement speed) the load impacts with a sunflower basket, resulting in shedding of seeds. The values of mass and distance of removal of the load were set to equivalently ensure the speed of the load at the time of impact on the sunflower stalk in the range of 0.5-1.5 m/s in laboratory conditions, which is adequate to the impact force of the reel blade on the stem in the field.

An experimental device was developed (Fig. 1) to determine the losses of sunflower seeds from force factors arising from the action of the reel blade on the stem.



a) *b*)

Fig. 1 - Experimental device

a – scheme of device; b – a general view; 1 – base; 2 – rack; 3 – pendulum; 4 – installation sector; 5 – sunflower plant; 6 – wireless accelerometer sensor

The laboratory device consists of a base *1*, a rack *2*, a pendulum *3* with a fixed load and a sector *4* with marks for the angle of rotation of the pendulum.

A wireless accelerometer sensor (Fig. 2) and a device for receiving, processing and transmitting a signal were developed to fix the force factors on the sunflower stem. Software has been developed for receiving and recording, as well as for visualizing data from the accelerometer sensor (Fig. 3).

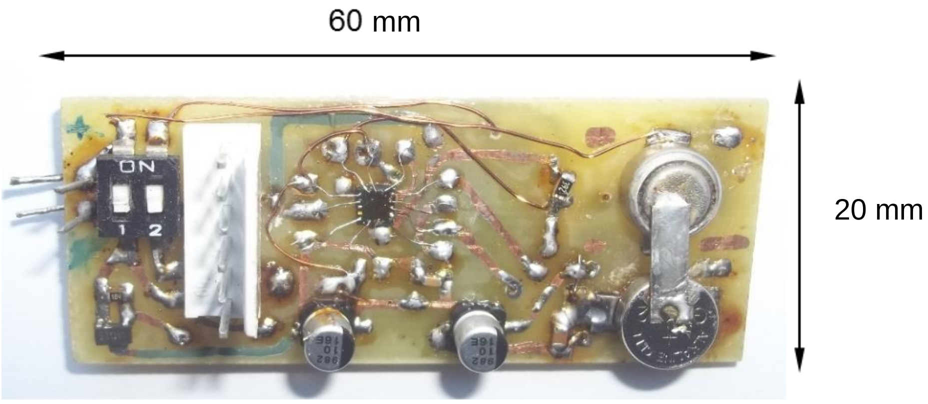


Fig. 2 - General view of the accelerometer sensor

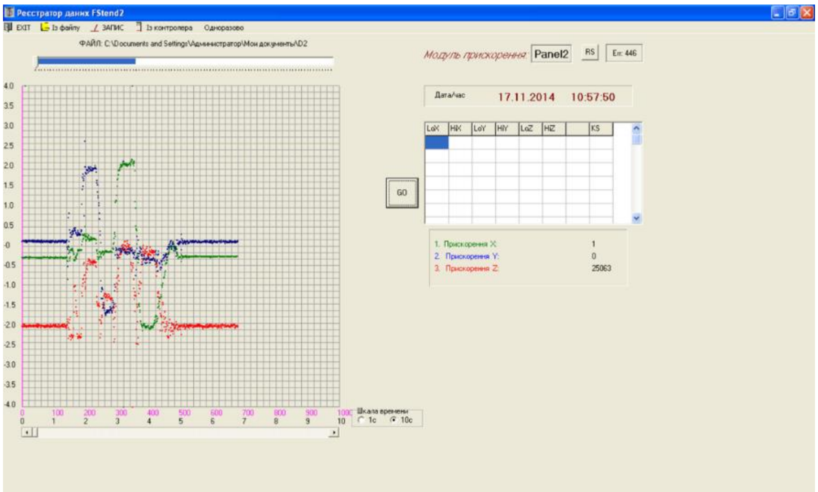


Fig. 3 - Software interface for recording and visualizing data from an accelerometer sensor

The operation of the device proceeded as follows. The sunflower plant was fixed in a latch. An accelerator sensor was installed on it as the nearest to the basket or on the basket itself. The pendulum weight was taken to a certain angle, (from 10º to 30º, which corresponded to the maximum speed of the weight from 0.5 to 1.5 m/s) turned on the software, and released the pendulum. The accelerations were automatically fixed in three planes after the impact of the pendulum load on the plant. After a complete stop of the plant movement we collected the seeds that spilled out and weighed them. The loss of sunflower seeds was determined as the ratio of the mass of seeds that fell from the basket from the impact to the mass of seeds in the basket before the impact:

$$w = \frac{m}{m+M} \cdot 100\%, \tag{1}$$

Where:

m is the mass of sunflower seeds that fell from the basket after the impact of the pendulum, g;

M - mass of sunflower seeds left in the basket after the impact of the pendulum, g.

The mass of sunflower seeds remaining in the basket after the impact of the pendulum was determined by threshing and weighing it.

The studies were planned and carried out according to the methodology of a three-factor experiment. The variable factors were the speed of impact of the pendulum on the stem V, the moisture content of sunflower seeds w, the coefficient of the ratio of the reel contact height to the average value of the sunflower height k. The loss of sunflower seeds from shedding Z was taken as an optimization function. The repetition of experiments was three times.

Table 2 shows the variable factors and their levels of variation.

Table 2

Variable factors and limits of their variation for determining the sunflower seeds loss from shedding under the impact to the sunflower stem

Factor	Value	Encoded value	Limits of variation	Levels of variation		
				lower	middle	upper
Speed of pendulum impact on the stem, m/s	V	X_1	1.0	0.5	1.0	1.5
Moisture of sunflower seeds,%	w	X_2	4.0	6.0	8.0	10.0
The ratio of the point of impact height to the average sunflower height	k	X_3	0.4	0.4	0.6	0.8

Cochran's test was used to check the reproducibility of the experiments. The adequacy of the regression equation was checked using the Fisher test. The assessment of the significance of the regression coefficients was performed using Student's t-test. Statistical processing of the results of experimental studies was carried out according to the procedure (*Hailis & Kovalev, 1994*). The results of the experimental study were processed using the Statistica 10 package.

RESULTS

As a result of experimental studies and statistical processing, an array of values of the sunflower seeds loss from shedding under the impact to the sunflower stem was obtained which are presented in Table 3.

Table 3

Calculated matrix of the loss of sunflower seeds from shedding by the Box–Behnken design for a three-factor experiment

Experience number	X_1	X_2	X_3	*Z, %*
1	+1	+1	0	0.44
2	+1	-1	0	2.15
3	-1	+1	0	0.15
4	-1	-1	0	0.87
5	+1	0	+1	0.80
6	+1	0	-1	0.86
7	-1	0	+1	0.20
8	-1	0	-1	0.24
9	0	+1	+1	0.18
10	0	+1	-1	0.22
11	0	-1	+1	1.03
12	0	-1	-1	1.11
13	0	0	0	0.53

The multiple regression model was applied to the obtained data. The coefficients of the regression equation were estimated by their significance and non-significant ones were excluded. As a result of statistical processing of experimental data, a regression mathematical model was obtained that adequately reflects the dependence of seed losses *Z* on the selected factors:

$$Z = 4.56507 - 1.15141 \cdot w + 4.50658 \cdot k + 0.35184 \cdot V^2 + 0.05567 \cdot w^2 - 3.87007 \cdot k^2 \quad (2)$$

Where V is the speed of the pendulum impact on the stem, m/s; w is the moisture content of sunflower seeds, %; k is the ratio of the reel contact height to the average sunflower height.

The graphic dependence of seed shedding on the speed of impact of the pendulum on the stem and seed moisture is shown in Fig. 4.

From the obtained dependences, it can be concluded that with an increase in the moisture content of the sunflower material and a decrease in the speed of impact on the sunflower heads, the loss of seeds is significantly reduced to 0.15–0.3%. At the same time, the losses increase to values from 1% to 2% at moisture values from 6–8% and impact speeds from 1–1.4 m/s. Also the value of the coefficient *k* affects the loss of sunflower seeds the rational values of which, according to the obtained graphical dependencies vary within 0.6-0.65. With such values the loss of sunflower seeds does not exceed 1% subject to rational values of the impact speed of 1–1.2 m/s and the moisture content of sunflower seeds of 7.5–8%.

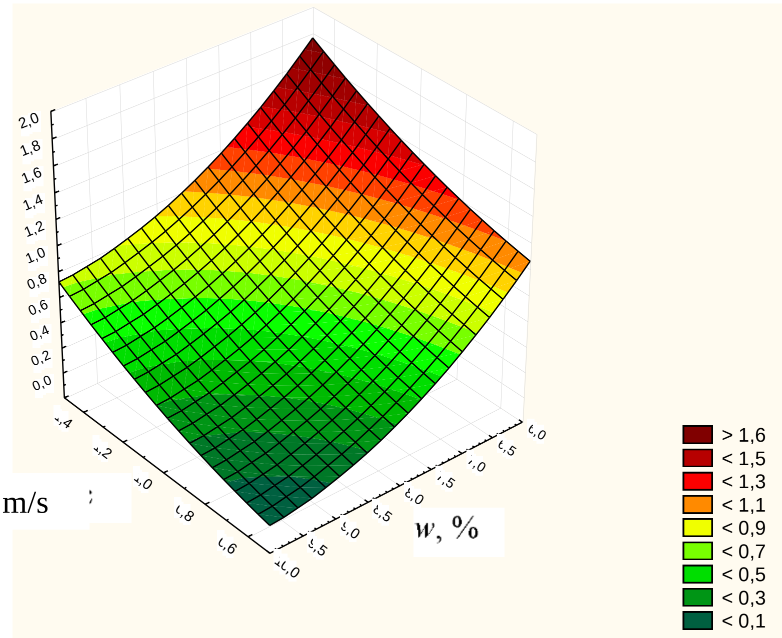


Fig. 4 - Dependence of sunflower seeds losses Z on impact velocity V and material moisture content w at *k* = 0.6

Since there is a relationship between the speed of impact of the reel blade on the sunflower stalk and the shedding of seeds from the basket, the obtained dependence (2) made it possible to establish the influence of the reel parameters on the quality indicators of its work.

The use of dependence (2) together with the developed mathematical model of the interaction between the reel blade and the sunflower *(Xu L. et al, 2019)* makes it possible to evaluate the influence of the parameters of the harvester header on the value of seed losses from shedding. Conducted mathematical modeling made it possible to substantiate the rationale parameters of the shovel reel of the header for sunflower seed harvesting which are: the curvature of the shovel reel S = 750 mm; number of reel shovels three; the ratio of the circular speed of the blade to the speed of the combine 1.25–1.3.

These parameters of the reel of the selection combine harvester provide a smooth capture of sunflower stalks with the minimum expected seed shedding values not exceeding 0.8–1.2%.

To reduce seed losses from shedding, dividers in the form of open boxes are installed on the header. Sunflower seeds spilling out of the baskets fall into the box and are subsequently sent to the header platform when it is raised.

Sunflower is grown with a row spacing of 700 or 450 mm on selection and seed plots. Proceeding from this the following scheme for placing dividers on the header bar of the Sampo-500 plot combine was proposed (Fig. 5).

The level of sunflower seed loss reduction from shedding from baskets can be estimated as the ratio of the total width of all dividers installed on the header to the width of the header. It has been experimentally established that losses of sunflower seeds from shedding from baskets decrease by 82 – 85% when using box-type dividers on the header of the Sampo-500 selection combine harvester.

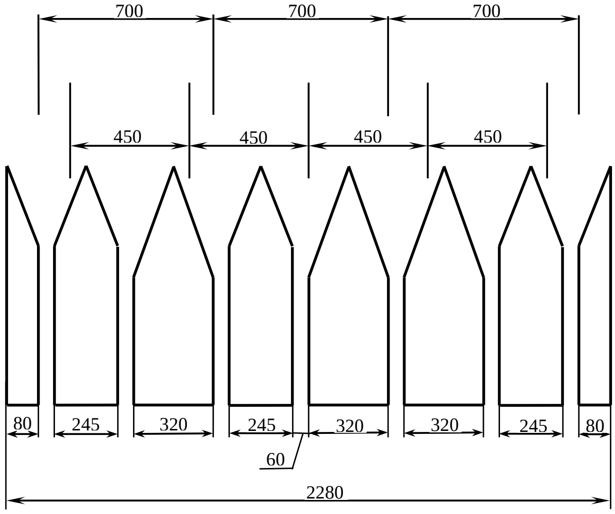


Fig. 5 - Layout of the dividers on the header bar

According to the results of the research the header attachment was developed for the Sampo-500 selection combine harvester (Fig. 6), consisting of box-type dividers, wind and side shields and a special three-bladed reel, the blades of which are made in the form of solid convex partitions. Due to this structure of the reel blades sunflower heads are fed evenly and smoothly during harvesting without sharp blows. They do not get pinched in the gaps between the blades and do not fall outside the header.

Fig. 6 - The design of the experimental header attachment of the "Sampo-500" plot combine for harvesting sunflower seeds

1 – reel bar; 2 – side divider; 3 – perforated sheet; 4 – box-type dividers

Due to the transparency of the blades and their convex shape, sunflower grain losses are reduced due to the possibility of easily adjusting the position of the reel in height relative to the sunflower heads. It also reduces the chance of cut heads getting caught in the reel blades and tipping over the header.

The header attachment works as follows. The dividers guide the sunflower plants into the reach of the reel blades as the combine moves across the field. Making a circular motion the reel blades enter the plant mass and incline the sunflower stalks and feed them along the dividers to the cutter bar of the header.

After being cut the sunflower heads are sent to the auger of the harvester and then enter the thresher of the combine.

The shape of the reel blades ensures their exit from the plant mass close to vertical which prevents the sunflower heads from tipping over the header. The closed space between the reel bars and the shaft does not allow the cut heads to catch on the bar and be overturned.

The experimental studies of the influence of operating modes on the quality indicators of the harvesting of seeds of sunflower crops were carried out to evaluate the developed header attachment.

As a result of processing the experimental data with using the Statistica 10 package a regression equation was obtained in the form of a polynomial of the second stage which adequately describing the dependences of the influence of the studied parameters on the amount of losses of free seeds Y_1 and seeds in baskets Y_2 (*Zareei et al, 2016*):

$$Y_1 = 8.2749 + 7.3478 \cdot V^2 - 1.3732 \cdot V \cdot K - 13.4644 \cdot V \quad (3)$$

$$Y_2 = 44.0099 + 28.3429 \cdot K^2 - 66.8215 \cdot K - 2.0533 \cdot V \cdot K \quad (4)$$

Where V is the ground speed of the combine, m/s; K is the kinematic mode index of the reel operation.

Kinematic mode index is defined as the ratio of the circular speed of the reel bar to the forward speed of the combine.

Graphs of the influence of the kinematic mode indicator on the value of losses of free seeds Y_1, seeds in baskets Y_2 and total losses Y are shown in Figure 7.

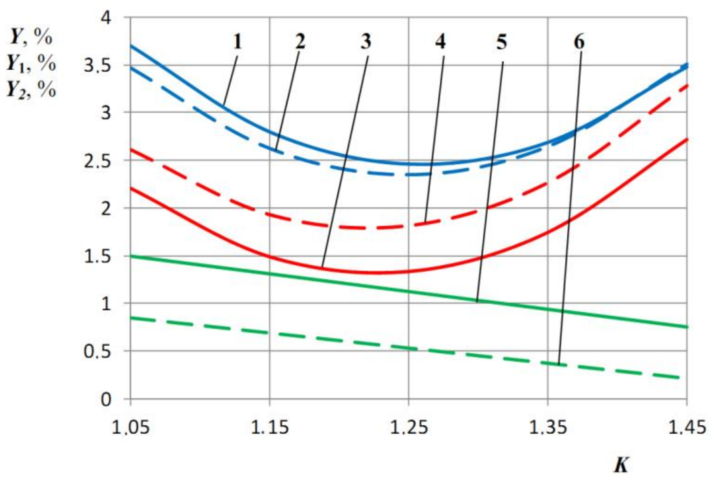


Fig. 7 - Graphs of the influence of the reel kinematic mode indicator on the loss of free seeds Y_1 (line 5 and 6), seeds in baskets Y_2 (line 3 and 4) and the total loss of sunflower seeds Y (line 1 and 2) for the harvester equipped with the developed header attachment

1, 3, 5 – V=1.1 m/s; 2, 4, 6 – V=1.35 m/s

From the analysis of the graphical dependencies of Figure 7, it was found that the ground speed of the combine has a decisive influence on the loss value of free seeds. The loss of seeds increases by 0.7–0.8% with an increase in the speed of movement from 1.1 to 1.4 m/s. An increase in the kinematic mode indicator K from 1.05 to 1.45 is accompanied by a decrease in the losses level by free seeds within 0.6–0.8%.

The minimum total loss of sunflower seeds is observed at the value of the kinematic mode index K = 1.24 – 1.27 in all speed modes, where the research was carried out.

A decrease in the K coefficient to 1.05 is accompanied by an increase in losses of both free seeds and seeds in baskets. This is due to the fact that at low values of the kinematic mode index of the reel, there is a deviation and breaking of sunflower plants forward in the direction of the combine and an increase in the probability of them falling onto a not mowed field.

Graphs of the influence of the ground speed of the combine on the value of losses of free seeds Y_1, seeds in baskets Y_2 and total losses Y are shown in Figure 8.

From the analysis of dependencies (Fig. 8) it was found that the value of the total losses of sunflower seeds varies within 0.35 – 0.4% over the entire range of changes in the ground speed of combine which the research was carried out. The minimum values of total losses are observed in the range of changes in the ground speed of the combine V = 1.15 – 1.25 m/s.

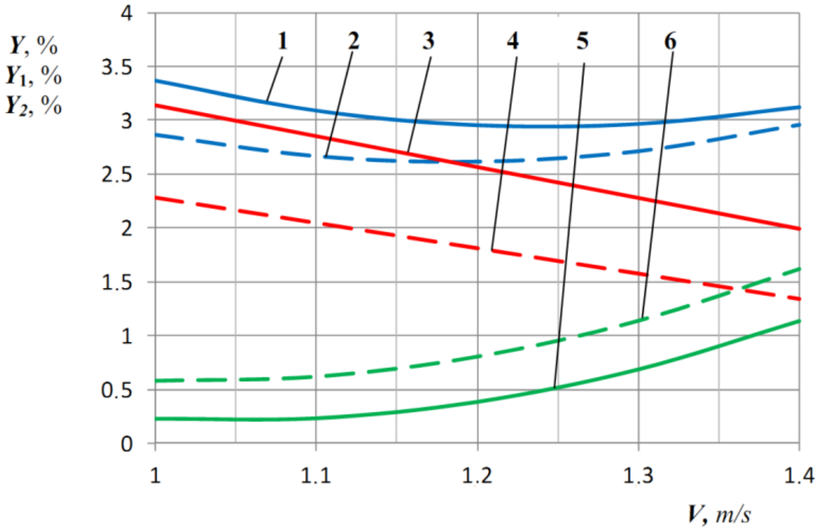


Fig. 8 - Graphs of the influence of the ground speed of the combine on the loss of free seeds Y_1 (line 5 and 6), seeds in baskets Y_2 (line 3 and 4) and the total loss of sunflower seeds Y (line 1 and 2) for the harvester equipped with the developed header attachment

1, 3, 5 – K=1.3; 2, 4, 6 – K=1.1

With an increase in the ground speed of the combine on the entire range of change, the loss of free seeds Y_1 decreases, and the losses in baskets Y_2 increase.

This is due to the fact that with an increase in the ground speed of the combine the conditions for the passage of plants through the channels of the dividers improve. That is the time for the combine to travel the distance between neighboring plants decreases and the probability of broken plants falling forward onto a not mowed field decreases accordingly. At the same time, it is necessary to increase the frequency of rotation of the reel with the increase in the speed of the combine. It leads to the overturning of the cut baskets by the reel through the windshield and forward to the not mowed field.

Thus, according to the analysis of the results obtained it was found that the loss of sunflower seeds in the baskets on the combine harvester equipped with the developed device is 2.4–3.6%. The main reasons for these losses are the uneven placement of sunflower baskets in height, and significant drooping of plants in the areas where the harvest was carried out. In addition, within 1.2–1.5% of the sunflower stems were broken and the baskets were on the soil surface. These plants could not be harvested with a header.

The minimum values of sunflower seeds losses behind the header with the developed attachment were 2.4–2.5%, with the value of the kinematic mode index 1.24–1.27. The use of the developed device will increase the harvesting volume of sunflower seeds by 5–7% compared to a standard combine harvester.

CONCLUSIONS

According to the results of laboratory field studies it was found that seed losses are significantly reduced to 0.15–0.3% with an increase in the moisture content of the sunflower material and a decrease in the speed of impact on the sunflower heads. At the same time the losses increase to values from 1% to 2% at humidity values from 6–8% with an increase in impact velocity from 1 m/s to 1.4 m/s respectively.

Mathematical modeling made it possible to substantiate the rational parameters of the shovel reel of the header for sunflower seed harvesting which are: the curvature of the shovel reel S = 750 mm; number of reel shovels three; the ratio of the circular speed of the blade to the speed of the combine 1.25–1.3.

The developed header attachment allows the combine harvester to be used on selection and seed plots of sunflower with a row spacing of 700 mm or 450 mm, providing a smooth grip on the stalk with minimum expected values of seed shedding, not exceeding 0.8–1.2%.

The influence of the operating modes of the developed header attachment on the quality indicators of the collection of seeds of sunflower crops has been experimentally studied. It was found that minimum values of sunflower seeds losses behind the header with the developed attachment were 2.4–2.5%, with the value of the kinematic mode index 1.24–1.27. The use of the developed device will increase the harvesting volume of sunflower seeds by 5–7% compared to a standard combine harvester.

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