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Shape Optimization of Concave Crossbars to Increase Threshing Performance of Moist Corn Ears

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Abstract: Harvesting of high-moisture corn ears poses a challenge due to the high level of grain damage. In the present study, a series of concaves adapted to moist corn ears threshing was developed and evaluated. The key improvements include a concave arc shape and oblique crossbars to reduce corn grain damage and threshing losses. Results show that the geometrical shape of the concave arc and its crossbars have a significant influence on the grain detachment from the ears, grain separation through the concave, and grain damage during the threshing process of moist ears of corn. Studies show that replacing the concave rounded crossbars with oblique ones can increase threshing performance of moist corn ears. A concave with an Archimedes' spiral arc and oblique concave crossbars is an effective approach to improve corn grain quality and reduce harvest losses due to grain damage. We identify the optimal design for threshing corn ears as an experimental concave with an Archimedes' spiral arc of 8 mm height, with 19 mm wide crossbars of the concave with an oblique working plane (tilt angle 25°). This design achieves minimal threshing grain losses (0.03%) when threshing moist ears (grain moisture content ~35%), and damaged grain in the threshing apparatus does not exceed the permissible limit of 3% at an ear feed rate of 16.8 kg s^{-1}.

Keywords: combine harvester; threshing cylinder; concave design; corn; grain separation

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1. Introduction

Corn (*Zea mays* L.), also called maize, originated in central Mexico 7000 years ago from wild grass and was one of the first crops cultivated by farmers [1,2]. Corn is grown throughout the world. It occupies 193.6 million ha (8.90 million ha in the EU alone) in area, and the average grain yield is 5.78 t ha^{-1} (7.50 t ha^{-1} in the EU). A total of 1119.7 million tons (66.7 million tons in the EU) of corn grain were harvested in 2020 [3]. Corn is the most versatile cereal crop in the world owing to its high yield and importance in food, chemical purposes, and livestock feed [4], as well as its widespread application in the pharmaceutical industry [5]. Corn grain contains approximately 72% starch, 10% protein, and 4% fat, supplying an energy density of 365 kcal/100 g [1].

In the Baltic Sea region, meteorological conditions for corn harvesting are unfavorable at the end of October [6,7]. The most suitable harvester for corn is a combine harvester with an axial threshing-separating rotor or with a tangential threshing device and rotary separators [8]. In Baltic countries, corn ears are mostly threshed using tangential threshing devices with modified concaves [9] and covered gaps between the adjacent rasp bars of the threshing cylinder [10].

Corn grain reaches its physiological maturity at 35% moisture [11,12]. In Western countries, corn is harvested when the moisture content of the grain is approximately 25% [13]. Corn plants cultivated for grain production must be harvested when the grain moisture content does not exceed 28% [14]. In Baltic countries, early varieties of corn ears manage to produce mature grains, and the moisture content in these grains during harvesting reaches up to 35–40% [6]. In especially favorable meteorological conditions, the moisture level in corn grain decreases to 26–28%.

To ensure optimal performance of a combine harvester during corn harvesting, the header, threshing apparatus, cleaning shoe, straw chopper, and other mechanisms require specific reconstructions and adjustments [15–17]. The most important mechanism of a combine harvester is the threshing apparatus and its structural characteristics (shape of the cylinder and rasp bars, shape of the concave arc and its crossbars) as well as technological parameters (feed rate, concave clearance, and peripheral velocity of threshing cylinder rasp bars). Setting well-balanced technological parameters to adjust the threshing apparatus increases the throughput of the combine harvester and improves the qualitative performance indicators of the threshing process, and grain separation through the concave [18,19]. Critical qualitative evaluation indicators of the combine harvester operation when harvesting corn ears include grain losses, grain damage, work efficiency, and fuel consumption [7,8,20]. Under ideal meteorological conditions, the permissible grain losses of a combine harvester during corn grain harvest must not exceed 1% [20]. These include combine harvester header grain losses of 0.4%, threshing losses of 0.1%, and separator and cleaning shoe losses of 0.5% [21]. Paulsen et al. [22] suggested that the permissible threshing losses are higher under real conditions, but must not exceed 0.3%. Experimental results show that under realistic conditions, the overall yield loss of corn grain is around 4% [22,23].

Total grain losses are mainly dependent on the corn ear feed rate, i.e., the speed of the combine harvester and the design of the threshing apparatus, among other technological parameters [17,20]. Threshing grain losses can be reduced by increasing the cylinder rasp bars' peripheral velocity [7]; however, this causes a significant increase in grain damage [24]. Therefore, the above-mentioned technological parameters must be optimized.

The total amount of grain injured by the combine harvester working parts during corn harvesting must not exceed 2–4%, depending on harvesting conditions [9,10,20,24]. Based on the level of grain damage, damaged grain can be divided into three categories: cracked, defected, and broken grain [25]. At grain moisture contents >30%, cracked grain accounts for about 43% of all damaged grain resulting from the impacts of the rasp bars of the threshing cylinder [20]. These data are similar to those published by other authors [13]. Corn ear threshing efficiency and grain damage depend on corn varieties [26], the moisture content [25,27,28], and the degree of maturity of the crop [29]. Furthermore, corn grain damage increases when harvested at negative temperatures [30,31]. Therefore, it is critical to choose the optimal time for harvesting corn [23,30].

Špokas et al. [20] investigated the influence of corn ear feed rate on grain damage. They found that damage depends on the corn ear movement along the concave surface. When the feed rate is too low (~10 kg s^{-1}), corn ears move slower along the surface of the concave, resulting in higher grain damage [9]. When the feed rate is excessive (over 20 kg s^{-1}), the concave becomes overloaded and reduces the movement speed of corn ear, resulting in higher grain damage [20].

Numerous researchers found that corn grain damage is influenced by the rotational speed of the threshing cylinder [7,24,32]. Bumbar et al. [30] established that the quality of threshing associated with the reduction of grain damage can be achieved by setting the tangential threshing cylinder rotation speed to 400–500 rpm, or its peripheral velocity to 17–21 m s^{-1}. When threshing moist ears, the peripheral velocity of the threshing cylinder must not exceed 15 m s^{-1} [7,33].

Another important technological parameter for grain damage is the clearance between the cylinder rasp bars and the concave. This depends on the dimensions of the ears being threshed [8,9]. When threshing larger diameter ears, the clearance at the entrance of the threshing apparatus is 40–45 mm, while at the exit it is 30–35 mm [30]. When threshing corn ear of 45 mm maximum diameter, the clearance between the cylinder rasp bar and the first concave crossbar is 36 mm, which was calculated as the maximum corn ear diameter subtracted the average grain height (9.8 ± 0.2 mm). The clearance between the cylinder rasp bar and the last concave crossbar (22 mm) was calculated by adding half of the average grain height (5 mm) to the smallest ear diameter (17 mm) [9].

During cereal harvesting, the clearance between the cylinder rasp bars and the concave is subject to variation within a narrow range [8], and nonuniform variation of this clearance does not significantly affect the qualitative performance indicators of threshing. In corn ear harvesting, the clearance is about three-fold of that applied in cereal harvesting. Researchers [9,34,35] reported that a designed concave characterized by its surface line approximating the Archimedes' spiral leads to a more uniform clearance variation. Among these, the experimental study demonstrated that for high-moisture corn ear threshing, the surface line of the concave must correspond to a portion of the Archimedes' spiral, and the clearances between adjacent crossbars must be 62.5 mm [9]. However, in previous studies, rounded and rectangular crossbars were used in the concave covering of the cylinder, which has a variable radius, similar to a portion of Archimedes' spiral.

Despite these findings, the role of the oblique concave crossbar has not been studied to date. Only one theoretical study investigated three different forms of concave crossbars: rectangular, rounded, and oblique [36]. The efficiency of the threshing process has been found to depend on the geometrical shapes of the concave crossbars. Numerical values of the reaction forces were found to be at their maxima in the oblique design of concave bars. Accordingly, it seemed possible that the threshing process at the first corn ear contact with the rasp bar will be more effective. The pilot experiment method has been applied to verify the adequacy of the mentioned designed theoretical models. The conducted research has substantiated the conclusions of the theoretical analysis, suggesting that a variable radius concave with a working plane tilt angle of the oblique crossbar equal to 45° would be the most rational option for corn ear threshing [37].

Therefore, it would be reasonable to further focus on experimental studies to determine the effect of the concave crossbars' shape on the grain damage due to the impact of the concave (circular or similar to a portion of Archimedes' spiral) by threshing moist corn ears.

2. Materials and Methods

2.1. Corn Ear Threshing Concaves

A stationary tangential single-concave threshing bench (Figure 1), designed and constructed at the Agricultural Machinery Technological Processes Research Laboratory (Vytautas Magnus University, Lithuania), was used for the experimental studies. The stand consisted of a 10 m long and 0.8 m wide conveyor belt for feeding the flow of corn ears into the threshing apparatus (1); a ten rasp bars tangential threshing cylinder (2), which was 1.5 m wide and 0.8 m in diameter, and had a wrapping concave (3). The mass of the threshing cylinder was 283.7 kg. Its moment of inertia, determined by the Autodesk Inventor Professional computer program, was 26.15 kg m^2. Three containers (11–13) were placed under the concave, receiving a mixture of grain and impurities (parts of corn cobs, stalks, husks, and silks) that passed through the individual sections of the concave. The tanks divided the concave into three equal areas (0.45 m^2 each) of sections I, II, and III. The mixture of grain and impurities, which was not passed through the concave's grate, was conveyed by means of a beater cylinder (4) to a collecting container (6).

In this study, we conducted comparative experimental studies on two concaves of different shapes (Figure 2). The overall dimensions of the two manufactured concaves are 1481 × 990 mm.

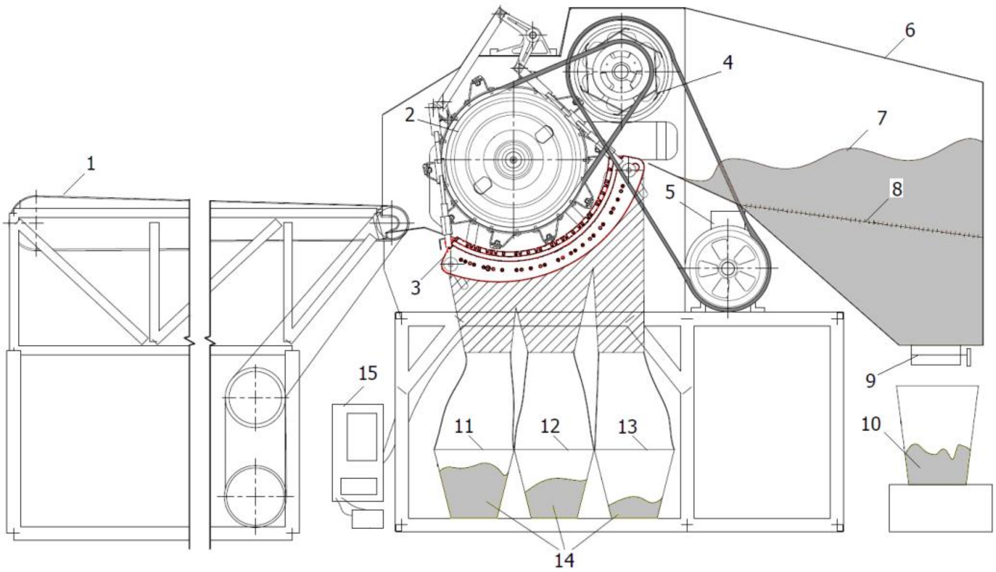
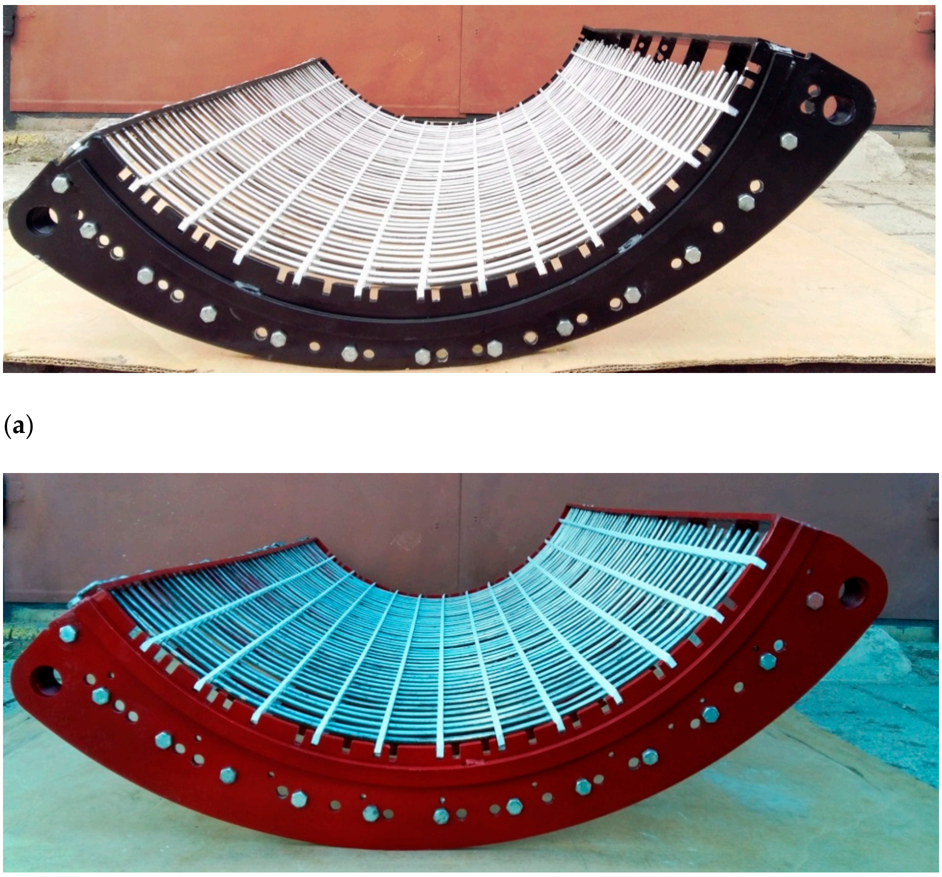


Figure 1. Test bench for corn ear threshing. 1—conveyor belt; 2—threshing cylinder; 3—control or experimental concave; 4—beater cylinder; 5—electric motor; 6—threshed matter container; 7—threshed matter; 8—sieve; 9—valve; 10—grain separation losses in the threshing unit; 11–13—grain containers, where a mixture of grain and impurities, passed through the individual sections I–III of the concave; 14—grain with impurities; 15—variable frequency drive (VFD) controller.



(**a**)

(**b**)

Figure 2. Concave: (**a**) experimental (similar to a portion of Archimedes' spiral), (**b**) control (circular).

The side frame parts forming the arc are cut using a CNC plasma cutter. The exact x and y coordinates of the points of the concave arc line (Figure 3) were calculated by entering the values into a system of equations [9]. The data from the calculations were transferred to the Mach 3 program, which controlled the working parts of the CNC plasma cutter.

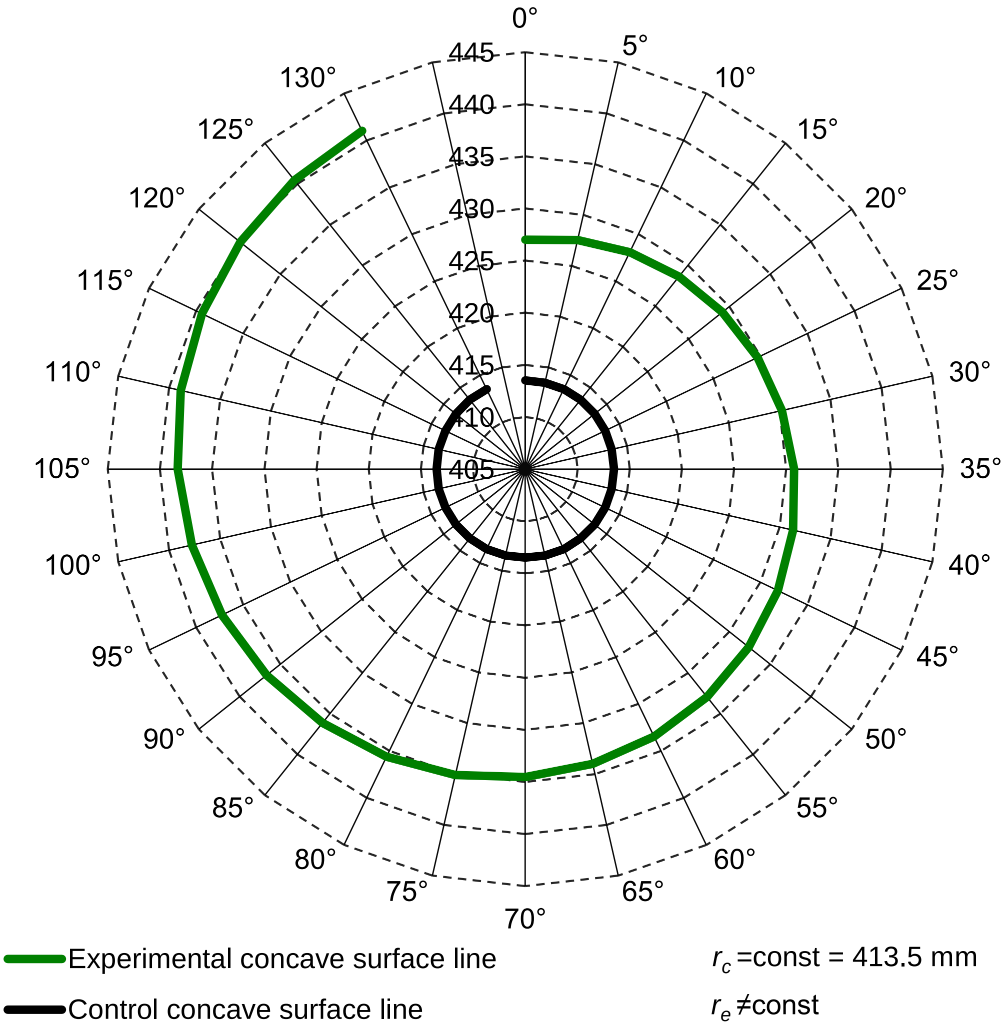


Figure 3. Control and experimental concave arc lines in the polar coordinate system.

The radius r_c of the control concave was constant (r_c = const = 413.5 mm), i.e., the arc of the concave's working surface was part of the arc of a circle (Figures 2b and 3). The arc of the experimental concave working surface was obtained assuming that $r_e \neq$ const. A polar coordinate system is used to construct the equation for this concave, with a uniformly decreasing angle of the wrapping line (Figure 3). This is achieved using the expression for the Archimedes' spiral equation in the polar coordinate system:

$$r(\theta) = a + b\theta, \tag{1}$$

where θ is the tilt angle at the selected point; a is the first reference coordinate of the arc of the spiral; b is a real variable describing the change of the spiral from angle θ.

An experimental concave arc line in the polar coordinate system is shown in Figure 3. It is obtained by adding the parameters of the threshing cylinder and the concave to Equation (1); the sum of the components is exchanged for the difference, as in this case the curve is being drawn in a steadily decreasing direction:

$$f(r) = r_1 - \Delta r \cdot \beta_n, \tag{2}$$

where r_1 is the first coordinate of the concave reference point (Equation (3)); Δr denotes the change of the radius within one degree (Equation (4)); β_n is the wrap angle of the concave around the cylinder at a chosen point.

The first coordinate of the concave reference point is the largest distance from the cylinder to the concave (i.e., the distance between the cylinder rasp bar and the first crossbar of the concave). This coordinate is described by the sum of the radius of the cylinder and the assumed distance between the cylinder and the concave:

$$r_1 = r + a_1, \tag{3}$$

where r is the radius of the cylinder (400 mm); a_1 is the highest distance between the cylinder and the concave (36 mm);

$r_1 = 400 + 36 = 436$ mm.

A change of one degree in the radius describes the change in the distance between the cylinder and the concave:

$$\Delta r = \frac{a_1 - a_2}{\beta}, \tag{4}$$

where a_2 is the smallest distance between the cylinder and the concave (a_2 = 22 mm); β is the angle of the arc of the concave (β = 123°);

$\Delta r = \frac{36-22}{123} = 0.114$ mm/°.

The variation in the clearance between the cylinder rasp bars and both concave crossbars along the concave length is presented in Steponavičius et al. [9].

2.2. Concave Crossbars

The surface line of the control concave fabricated for this study was part of the arc of the circle (Figure 4b), while that of the experimental concave was part of the Archimedes' spiral (Figure 4a,c). In both concaves, the gaps between adjacent crossbars could be changed (45.0, 62.5, and 80.0 mm); however, in this study, they were held constant at 62.5 mm.

Five differently shaped crossbars were designed and fabricated for this study (Figure 5) and mounted in the concaves (Figure 2). The height of the crossbars above the longitudinal bars of the concave was the same (8 mm). The width of the crossbars on the rectangular and rounded working plane was 8 mm. Three sets of crossbars had an oblique working plane: one set had a tilt angle of 45° and a width of 8 mm, the second set had a tilt angle of 25° (width B = 19 mm), and the third set had a tilt angle of 11° (width B = 41 mm) (Figure 5).

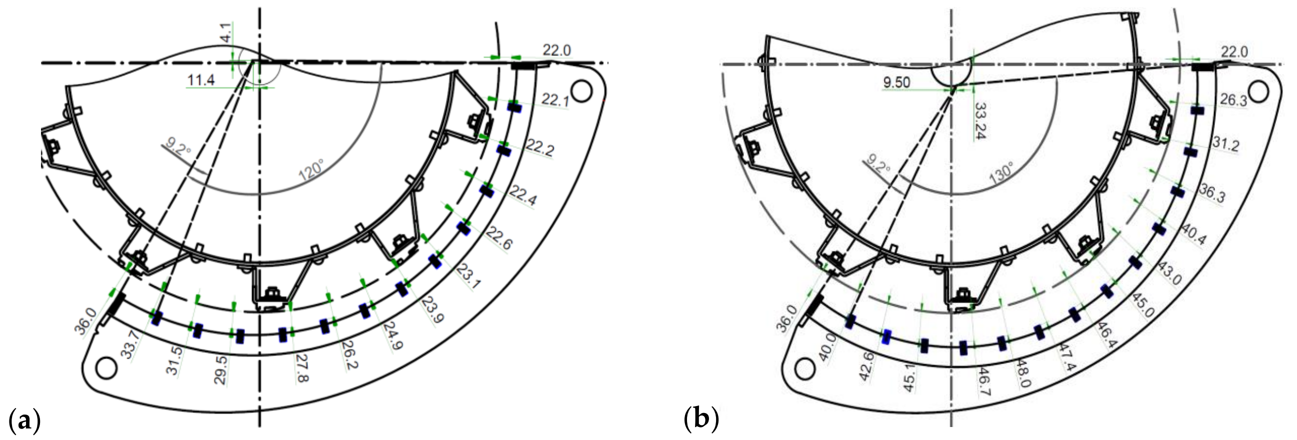


Figure 4. *Cont.*

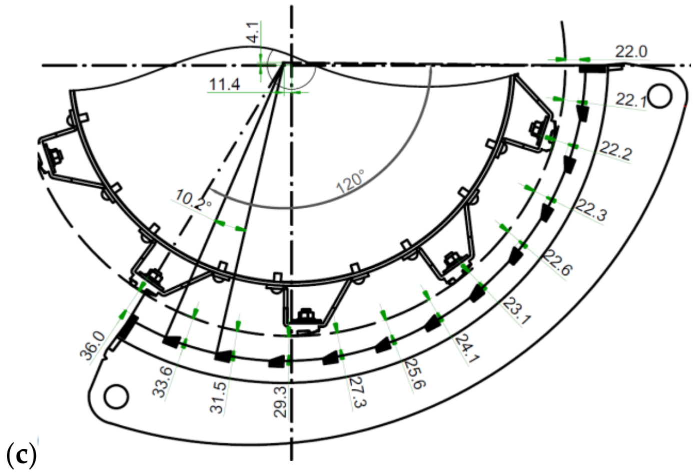


Figure 4. Concaves of threshing cylinder with 62.5 mm spacing between crossbars (**a**) experimental, number of crossbars N = 14 units, width B = 8 mm, (**b**) control, N = 15 units, width B = 8 mm, (**c**) experimental, N = 11 units, B = 19 mm.

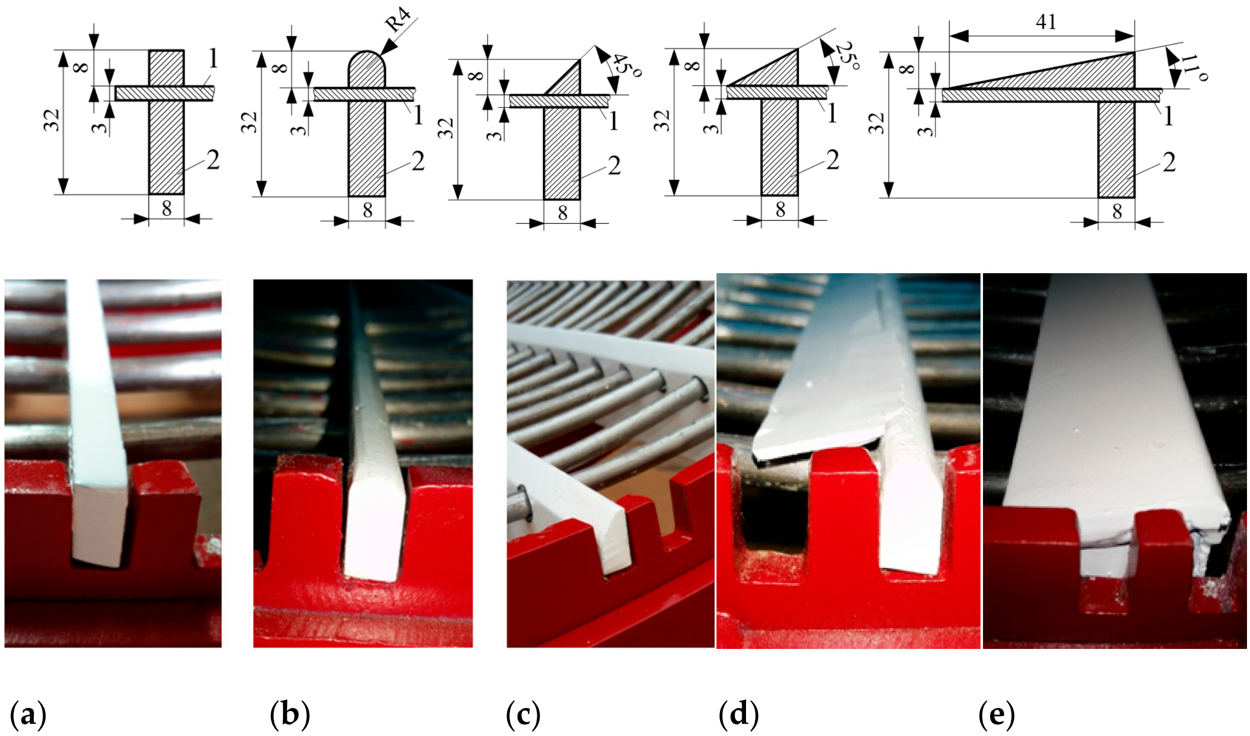


Figure 5. Concave crossbars: 1—concave rod; 2—concave crossbar; (**a**) rectangular; (**b**) rounded; (**c**–**e**) oblique (tilt angle of the working plane of the concave crossbars is 45°, 25°, 11°, respectively).

The installation of different sets of crossbars in the concaves was accompanied by changes in the concave parameters, such as the active separation area (Table 1, Figure 4).

Table 1. Concave parameters.

Shape of Concave Arc and Crossbars		Total Area A, m^2	Active Separation Area A_s, %	Concave Arc Length L, m	Concave Arc Angle α, °	Wrap Angle of Concave Around Cylinder β, °	Clearances between Crossbars l, mm	Number of Crossbars, Units
Part of the circle (control concave)	Rectangular Rounded 45°	1.39	58.8	0.975	120	123	62.5	15
Part of the Archimedes' spiral (experimental concave)	Rectangular	1.34	59.1	0.910	130			14
	Rounded		59.1					14
	45°		59.1					14
	11°		32.2					9 *
	25°		45.1					11 **

* concave crossbars with oblique working plane, 11° tilt angle, and 41 mm width; ** concave crossbars with oblique working plane, 25° tilt angle, and 19 mm width. The width of all other crossbars is 8 mm.

In fact, the experimental concave had a shorter arc length of 65.0 mm, and therefore had one less crossbar than the control concave. The two shapes of concaves wrapped the threshing cylinder with the same 123° angle, while the concave clearance was 36–22 mm. The wrap angle of the concave around the cylinder would decrease with increasing clearance between the cylinder rasp bars and concave crossbars. The spacing between the cylinder and the experimental concave can be changed depending on the diameter of the corn ears. While a uniform variation of the spacing cannot be guaranteed, the deviation will not be significant.

2.3. Feed Rate, Cylinder Speed, and Concave Clearance

The tests were carried out for corn ears fed to the threshing apparatus at a feed rate of 16.8 kg s^{-1}. The corn ears were fed into the threshing apparatus by a 10 m long conveyor belt moving at 1 m s^{-1} (Figure 1). They were weighed on a *CAS DB-1H* electronic balance (with a maximum load of 60.00 ± 0.02 kg, and a minimum load of 400 ± 20 g), and evenly distributed over a 10 m long section of the conveyor belt.

The threshing cylinder mounted on the bench is driven by a 30 kW electric motor. The rotational speed of the threshing cylinder (350 min^{-1}) was set using a *Delta VFD-C2000 SERIES* variable frequency drive controller. This corresponds to a threshing cylinder rasp bars peripheral velocity of 14.66 m s^{-1}.

Taking into account the dimensions of the ears, at the beginning of both concaves used in the study (control and experimental), a gap of 36.0 mm between the first crossbar and the cylinder rasp bar was set. This gap was equal to 22.0 mm at the end of the concave.

In this study, the feed rate, cylinder speed, and concave clearance were constant.

2.4. Biometric Characteristics of Corn Ears

The experimental studies were carried out on a threshing bench in the laboratory (Figure 1), with dimensions equivalent to those of a modern combine harvester. Cultivars of *Recolt* (FAO 160/170), a high-moisture variety, were threshed at hard maturity. A sample of 30 ears was taken at random from each of the hand-picked ears in triplicate. Each ear was weighed individually, and the husk leaves were separated and weighed. The length and maximum diameter of each ear were measured. After the grains have been separated from the cobs of each ear, the grains and the cobs were weighed separately. The length of the cobs was measured. The main biometric characteristics of the corn ears were as follows: ear weight—225.14 ± 12.36 g, maximum ear diameter—46.89 ± 0.79 mm, ear length—173.56 ± 3.55 mm, maximum corn cob diameter—28.36 ± 0.53 mm.

The moisture content of grains, cobs, silks, stalks, and husk leaves was determined by drying in an induction oven until the moisture has completely evaporated [38,39]. The moisture tests were repeated five times. The moisture contents of grains, cobs, silks, stems, and leaves were 34.81 ± 0.39%, 59.67 ± 1.77%, 38.98 ± 1.89%, 62.54 ± 3.99%, and 34.99 ± 2.08%, respectively.

2.5. Indicators for Assessing Quality of Ear Threshing Process

The most important qualitative indicators for assessing the threshing process of corn ears are grain separation losses in the threshing unit, grain threshing losses, grain damage, and threshing power consumption. They depend on the design of the threshing apparatus, technological parameters, biometric characteristics of the ears, and the number of ears fed into the threshing apparatus [20,21,40,41].

Grain separation losses in threshing device. One of the most important indicators of the threshing process of corn ears is the grain separation losses—the grain that has been threshed, but that has not passed through concave grates and passes through to the straw walkers (rotor separators) of the combine harvester. Petkevichius et al. [7] stated that with the correct adjustment of the threshing apparatus, separation losses would not exceed 20% of the grain feed rate. Grain separation losses in the threshing device are considerably reduced by increasing the concave length, i.e., the separation area [42]. However, this possibility is almost exhausted in modern combine harvesters.

The concave of the threshing apparatus is divided into three parts: the first (beginning), the second (middle), and the third (end) (Figure 1). The lengths of the three parts were the same, at 0.325 m for the control concave and 0.317 m for the experimental concave. During the threshing of the ears, the grains that passed through the parts of the concave were collected in grain containers 11, 12, and 13. They were weighed using an electronic scale *CAS DB-1H* (*CAS*, Republic of Korea). Grain separation A was determined by separating the grains from the impurities and weighing them after they had passed through the individual concave sections. The debris (pieces of cobs, leaves, and threshed grain that did not pass through the concave grate) (7) dropped from the end of the beater cylinder (4) were collected in a threshed matter container (6). The grains were passed through a sieve (8) and collected in the container before being weighed separately.

After weighing the threshed grains, the separation losses K, or grain that falls on the straw walkers, was calculated as the separation of the grains in the threshing apparatus. Because the total mass of the grain is known after the test, i.e., after the entire flow of ears delivered to the threshing apparatus by the conveyor is threshed, it is possible to determine the percentage separation of the grain (A, %) through the different parts of the concave, as well as the separation losses (K, %).

Grain threshing losses. These losses comprise grains that have not been detached from the ear in the threshing apparatus. The losses of threshing grains are determined by removing the incompletely threshed ears from the threshed matter container 6 (Figure 1). The grain threshing losses (in grams) are determined by separating the unthreshed grains from the cobs of each ear and weighing them with a *Kern CM 320-1N* electronic scale (Kern, Germany). Knowing the total weight of the threshed grains, the percentage of grain threshing losses (N, %) is calculated.

Grain damage. To determine the damaged grain quantity, three samples of 200 g each were taken from containers 6, 11, 12, and 13 (Figure 1) and placed in bags. In the laboratory, three samples (100 g each) were separated from each bag. The visually visible mechanically damaged grains were separated and weighed using a *Kern CM 320-1N* electronic scale (Kern, Germany). In this work, only broken grains were evaluated, while cracked and defected grains were not. The average percentage of damaged grain (S, %) was calculated with these data.

Power required for rotation of cylinder when threshing corn ears. Numerous studies have already shown that the ear feed rate to the threshing apparatus [20,43,44] and the cylinder speed [45] increase the power required and thus the fuel consumption. The aim of this study was to determine the change in the power required for threshing corn ears after replacing the control concave with the experimental one. The power demand for the rotation of the threshing apparatus cylinder was measured simultaneously with two devices: a power analyzer *ME-MI2492* (Metrel, Slovenia) and an *Almemo 2890-9* (Ahlborn, Germany). The measurement limit is 0–150 kW, the value of the step is 0.1 kW, and the measurement error is $\pm 3\%$ of the numerical value of the determined power.

2.6. Statistical Analysis

The experiments were carried out with at least four replicates. The data were analyzed using analysis of variance (ANOVA) with *Statistica 10.0* statistical software. The post hoc test for the significant difference ($R_{.05}$) was used to compare the arithmetic means of the data. $R_{.05}$ was calculated with a 95% level of confidence [46].

3. Results

3.1. Losses of Grain Separation in Threshing Device

First, the grain separation through the grate of a control concave divided into three parts was studied. Losses of grain separation in the threshing apparatus are the losses of grains that have detached from the ear cob but have not been able to pass through the concave grate and therefore have fallen onto the straw walkers.

Comparative studies using a control (constant radius) concave (Figure 2b) and different crossbars (Figure 5a, b, c) showed that in the first part of the concave, the grain separation could be increased from 12.24% ± 1.66% (crossbars rectangular, B = 8 mm) to 20.15% ± 2.73% (oblique crossbars γ = 45°, B = 8 mm) (Figure 6).

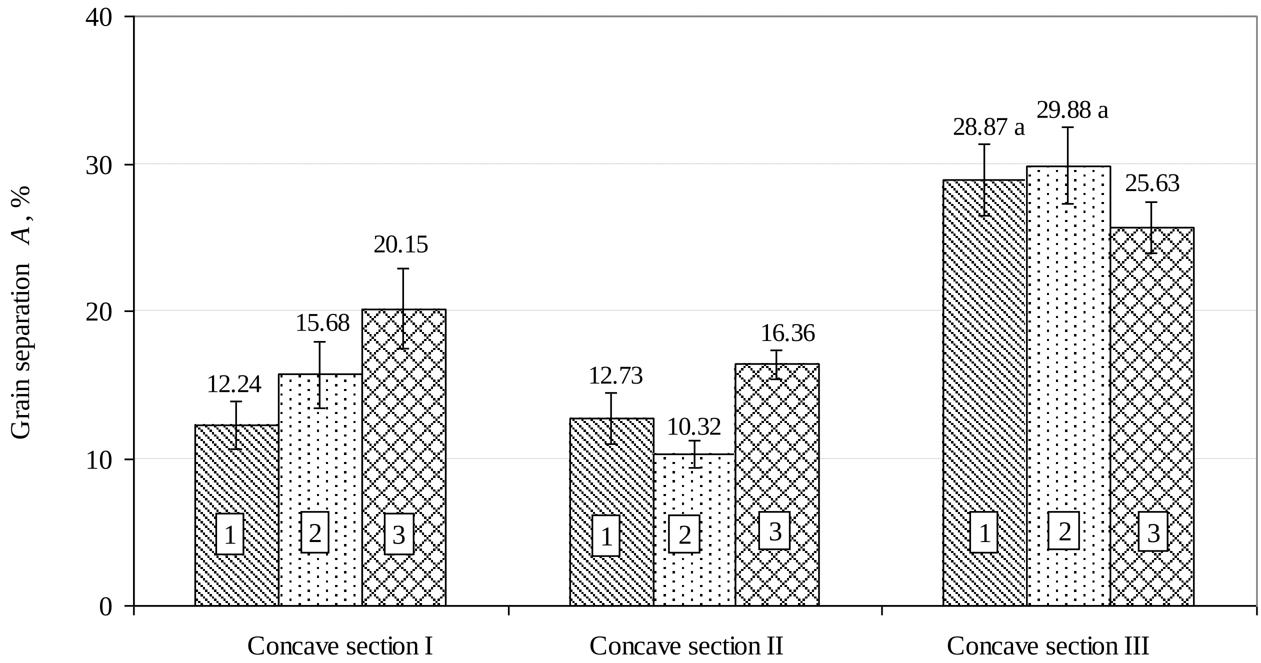


Figure 6. Influence of working plane shape of control concave crossbars on grain separation: 1—rectangular, B = 8 mm; 2—rounded R = 4 mm, B = 8 mm; 3—oblique γ = 45°, B = 8 mm. a—any two samples with a common letter are not significantly different (p > 0.05), as determined by one-way ANOVA.

In the second part of the concave, the lowest grain separation was obtained with the use of rounded crossbars. Then, 10.32% ± 0.90% of the grains passed through the concave grate. The grain separation in the second part varied from 12.73% ± 1.71% to 16.36% ± 0.99% using the other two shapes of crossbars. When evaluating the crossbars in terms of grain separation through the third part of the concave, the best results were obtained with rounded crossbars (29.88% ± 2.63%), and rectangular crossbars (28.87 ± 2.43%).

The results of the tests with the experimental concave showed that by replacing the crossbars of the rounded working plane with an oblique one, the grain separation in the first part of the concave could be increased from 12.9% ± 1.58% (oblique working plane crossbars γ = 11°, B = 41 mm) to 40.9% ± 2.80% (oblique crossbars γ = 45°, B = 8 mm) (Figure 7).

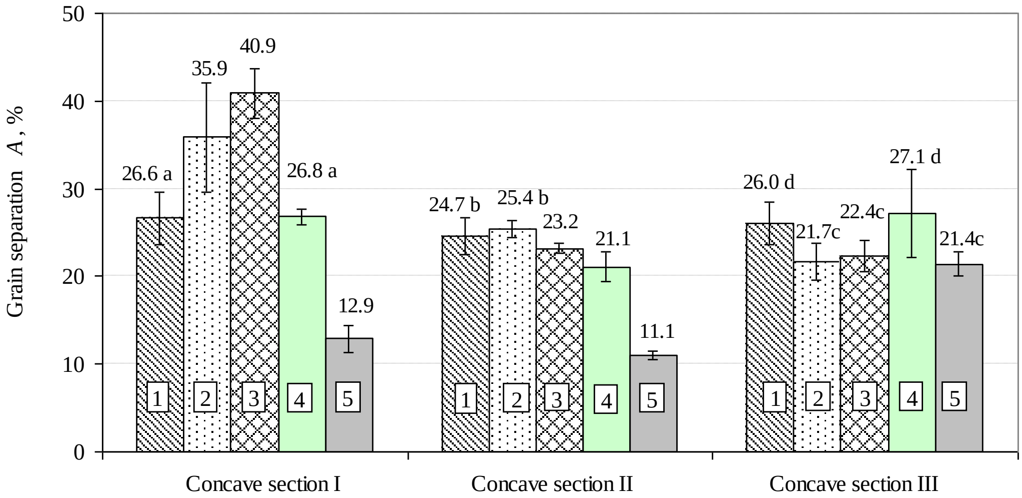


Figure 7. Influence of working plane shape of experimental concave crossbars on grain separation: 1—rectangular crossbars, B = 8 mm; 2—rounded crossbars R = 4 mm, B = 8 mm; 3—oblique crossbars γ = 45°, B = 8 mm; 4—oblique crossbars γ = 25°, B = 19 mm; 5—oblique crossbars γ = 11°, B = 41 mm. a, b, c, d—any two samples with a common letter are not significantly different (p > 0.05), as determined by one-way ANOVA.

In the second part of the concave, the lowest grain separation was obtained with the use of oblique working plane crossbars with γ = 11°, B = 41 mm (Figure 7). Then 11.1 ± 0.48% of the grains passed through the concave grate. The remaining four shapes of crossbars showed a small variation in the grain separation, from 21.1% ± 1.72% to 25.4% ± 0.92%. With regards to the crossbars, the best results were obtained with the rectangular crossbars (26.0% ± 2.49%), and oblique crossbars with γ = 25°, B = 19 mm (27.1% ± 5.02%).

In the control concave, using different shapes of crossbars, grain separation losses K on the straw walkers ranged from 27.87% ± 1.18% to 35.36% ± 4.70% (Table 2). The control concave with crossbars of γ = 45° had the lowest grain losses on the straw walkers (27.87% ± 1.18%). In the experimental concave with different shapes of crossbars, between 13.60% ± 3.06% and 53.67% ± 2.00% of the grains were deposited on straw walkers.

Table 2. Influence of concave crossbar shapes on grain separation losses (grains thrown on straw walkers) in threshing unit K, threshing losses N, and power consumption Q (q = 16.8 kg s^{-1}).

Shape of Concave Crossbars	Grain Separation Losses K, %	Threshing Losses N, %	Power Consumption Q, kW	Power Consumption Variation Coefficient v, %
Rectangular:				
control	33.08 ± 1.75 ^{a}	9.10 ± 3.25	15.23 ± 1.55 $^{e\,g}$	6.41
experimental	20.57 ± 0.52 ^{c}	2.08 ± 1.80 ^{d}	16.91 ± 2.94 $^{f\,g}$	10.94
Rounded:				
control	35.36 ± 4.70 ^{a}	6.01 ± 1.56	15.83 ± 1.11 ^{e}	4.39
experimental	16.73 ± 3.80 ^{b}	1.32 ± 0.21 ^{d}	17.79 ± 1.75 ^{f}	6.18
Oblique 45°:				
control	27.87 ± 1.18	4.77 ± 1.06	13.96 ± 0.59	2.65
experimental	13.60 ± 3.06 ^{b}	0	17.98 ± 0.36 ^{f}	1.26

Table 2. *Cont.*

Shape of Concave Crossbars	Grain Separation Losses *K*, %	Threshing Losses *N*, %	Power Consumption *Q*, kW	Power Consumption Variation Coefficient *v*, %
Oblique 25°:				
control	–	–	–	–
experimental	24.98 ± 6.33 [c]	0.03 ± 0.02	17.67 ± 0.74 [f]	0.81
Oblique 11°:				
control	–	–	–	–
experimental	53.67 ± 2.00	0.92 ± 0.88 [d]	18.23 ± 0.23 [f]	2.64

[a, b, c, d, e, f, g]–any two samples with a common letter are not significantly different ($p > 0.05$), as determined by one-way ANOVA.

3.2. Grain Threshing Losses

The control concave with rectangular crossbars on the working plane resulted in high threshing losses of 9.10% ± 3.25% (Table 2). The permissible limit for grain threshing losses (0.3%) exceeded over 30-fold. When the same rectangular crossbars were placed in the experimental concave, the losses were reduced by a factor of four to 2.08% ± 1.80%. When the threshing apparatus was equipped with an experimental concave with 25° oblique crossbars on the working plane, threshing grain losses were within the permissible limit. The experimental concave with 45° oblique crossbars did not result in any losses at all, although the same 45° oblique crossbars in the control concave resulted in losses of 4.77% ± 1.06%. The use of 11° oblique crossbars on the working plane in the experimental concave exceeded the permissible limit for threshing losses by three times.

3.3. Power Required for Rotation of Cylinder when Threshing Corn Ears

In the control concave, the change from rectangular to oblique crossbars results in lower power consumption (13.96 ± 0.59 kW). No significant difference was observed between the power requirement for the threshing apparatus using rounded and rectangular crossbars (Table 2).

The arc shape of the working plane of the experimental concave was found to increase the power required by about 2 kW. The power required for rotating the cylinder when threshing corn ears with rectangular, rounded, or oblique crossbars on the working plane of the concave was only slightly different at around 1 kW, i.e., around 6%. The highest power consumption of 18.23 ± 0.23 kW was obtained with the oblique crossbars (γ = 25°). The uniformity of the variation of the power demand, evaluated by the confidence interval of the arithmetic mean, was significantly higher at steady-state and with the use of the crossbars on the oblique working plane (Table 2).

3.4. Grain Damage in Threshing Apparatus

Grain damage in the threshing apparatus was investigated by analyzing the damaged grain that had passed through the three sections of the concave and the grain that had not passed through the concave grates but had fallen on the straw walkers and had been damaged during the threshing process.

The results of this study show that the installation of the rectangular crossbars in the experimental concave result in the lowest grain damage in the first section of the concave (1.97 ± 0.38%), while in the second and third sections the damage was equal to 3.00% ± 0.63% and 3.58 ± 0.58%, respectively (Figure 8). Among the grains that had fallen on the straw walkers, the damaged grain amounted to 4.90% ± 0.93%, and the total damage exceeded 3% (Figure 13).

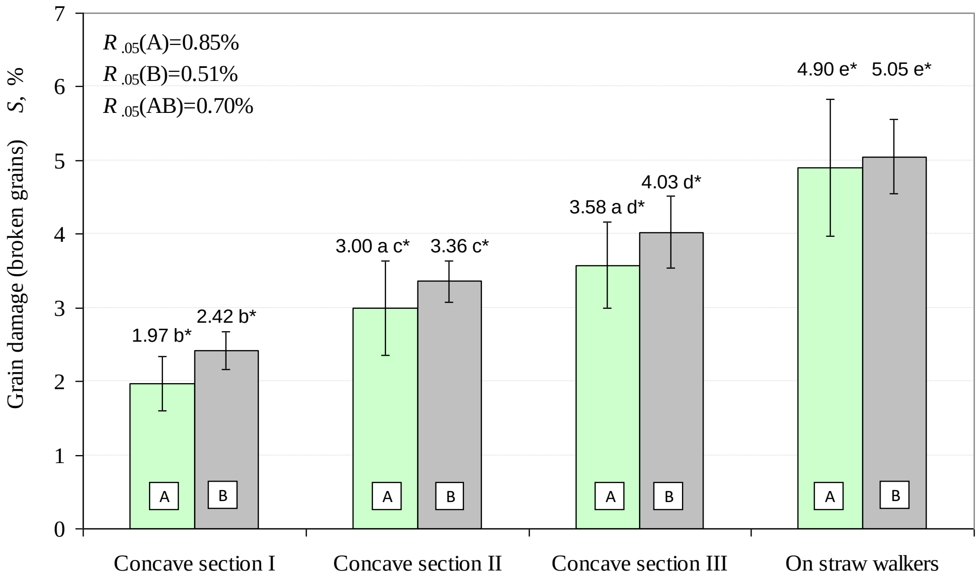


Figure 8. Influence of concave with rectangular crossbars on damaged grain. A—experimental concave; B—control concave. a, b*, c*, d*, e*—any two samples with a common letter are not significantly different ($p > 0.05$), as determined by one-way ANOVA (* is determined by two-way ANOVA).

The installation of rectangular crossbars in the control concave results in a slight increase in damaged grain in all parts of the threshing apparatus. The lowest damage was found in the first part of the concave, 2.42% ± 0.25%, with an increase toward the end of the threshing apparatus (Figure 8). In conclusion, the damage of corn grains in the threshing apparatus differs only slightly between the control and the experimental concaves, i.e., there is no statistically significant difference in the amount of damaged grain in different parts of the threshing apparatus.

In the experimental concave, changing the crossbars of the rectangular working plane to rounded ones results in the least damage to the corn grain in the first part of the concave, at 1.42% ± 0.33% (Figure 9). In the same part of the control concave, the grain damage was higher (1.80% ± 0.32%), though the threshold for a significant difference ($R_{.05}$ = 0.82%) was not exceeded when comparing the first parts of the two concaves. The highest percentage of damaged grain was found in the mass that fell on the straw walkers, amounting to 5.45% ± 0.45% in the control and 4.33% ± 0.53% in the experimental concave. Furthermore, a statistically significant difference was found when comparing the two concaves in terms of grains damaged in the mass on the straw walkers. The damaged grain quantity obtained using the experimental and control concave in the second and third parts of the concave and on the straw walkers exceeds the permissible limit of 3% (Figure 9). The total amount of grain damaged with the rounded crossbars is only slightly lower than with the rectangular ones (Figure 13).

The experimental concave with oblique working plane crossbars with $\gamma = 45°$ for corn ear threshing exhibited the lowest grain damage at 1.16 ± 0.32% in the first part of the concave (Figure 10). In the second and third parts of the concave, the damage increased from 2.11% ± 0.50% to 3.22% ± 0.70%, and on the straw walkers, it reached 4.64% ± 0.59%. The grain damage in the first part of the control concave (1.23% ± 0.28%) was similar to that of the experimental concave (the difference did not exceed the threshold of a significant difference of 0.60%).

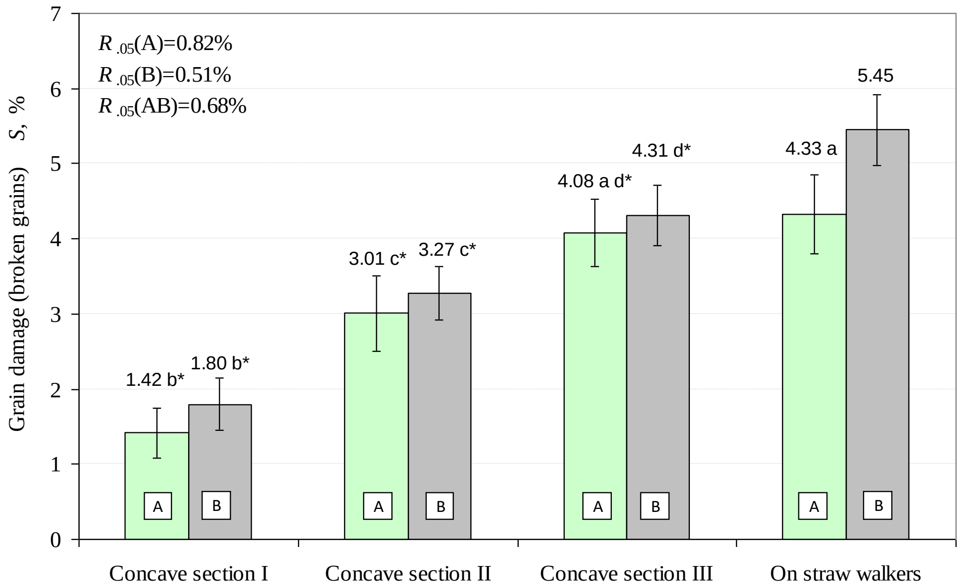


Figure 9. Influence of concave with rounded crossbars on damaged grain. A—experimental concave, B—control concave. a, b*, c*, d*—any two samples with a common letter are not significantly different ($p > 0.05$), as determined by one-way ANOVA (* is determined by two-way ANOVA).

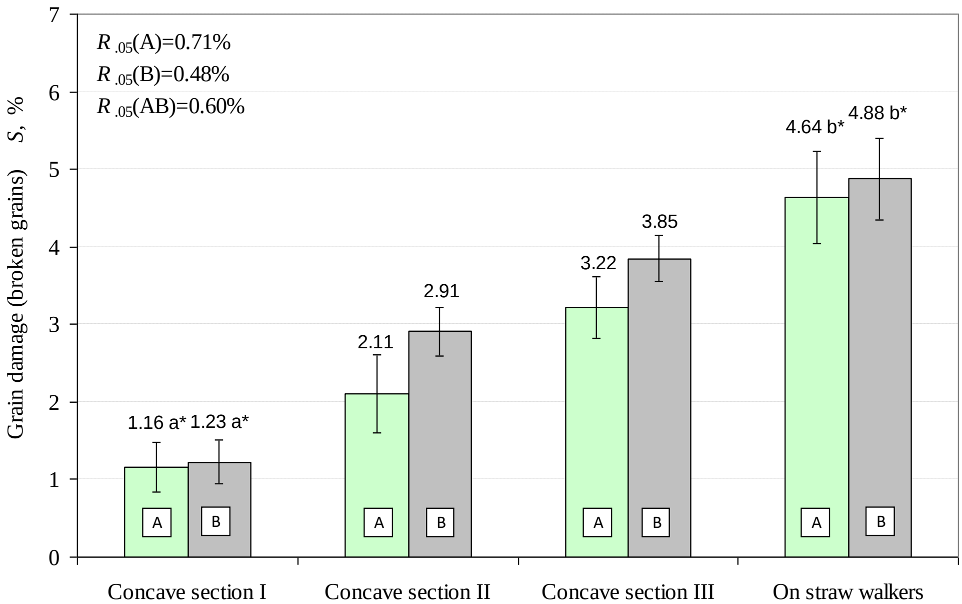


Figure 10. Influence of concave with oblique working plane (γ = 45°) crossbars on damaged grain. A—experimental concave, B—control concave. a*, b*—any two samples with a common letter are not significantly different ($p > 0.05$), as determined by two-way ANOVA.

When assessing the concaves in terms of grain damage in the second and third parts, significant differences were found in both cases. The total grain damage using the experimental concave with oblique working plane crossbars of γ = 45° did not exceed the permissible limit of 3%, being estimated at 2.78% ± 0.35% (Figure 13).

In the experimental concave, the installation of the oblique working plane crossbars of γ = 25° resulted in grain damage of 1.60% ± 0.33% in the first part of the concave, an increase to 1.86% ± 0.44% in the second part of the concave, and a slight increase to 1.88% ± 0.42% in the third part of the concave (Figure 11). No statistically significant difference was found between the damaged grains in the different parts of the concave. The total amount of damaged grain did not exceed the permissible limit of 3% (Figure 13).

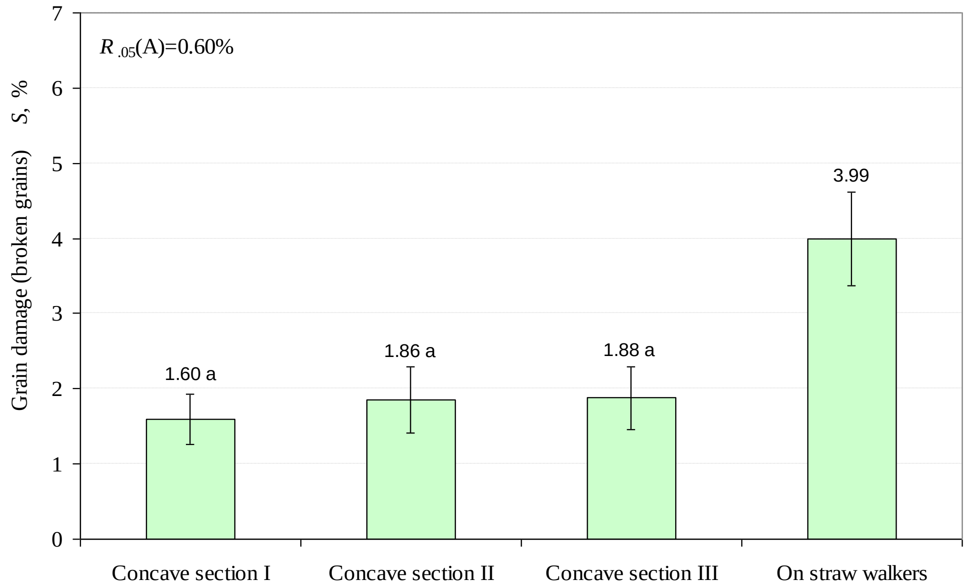


Figure 11. Influence of concave with oblique working plane (γ = 25°) crossbars on damaged grain. a—any two samples with a common letter are not significantly different ($p > 0.05$), as determined by one-way ANOVA.

Replacing the oblique working plane crossbars of the concave with crossbars with a lower tilt angle of 11° results in even less grain damage than with the use of crossbars with γ = 25° (Figure 12). The total amount of damaged grain with this experimental concave is 2.01% ± 0.28% (Figure 13).

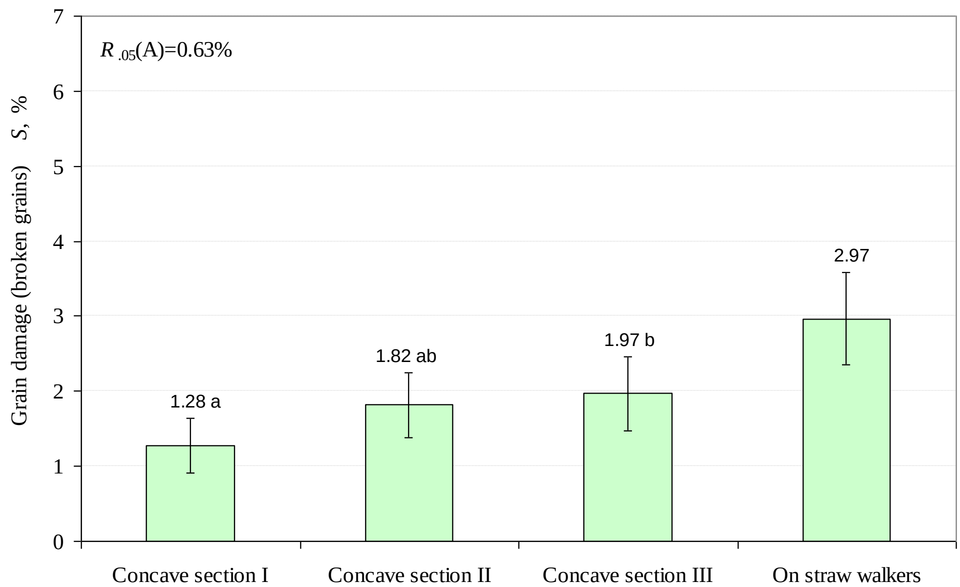


Figure 12. Influence of experimental concave with oblique working plane (γ = 11°) crossbars on damaged grain. a, b—any two samples with a common letter are not significantly different ($p > 0.05$), as determined by one-way ANOVA.

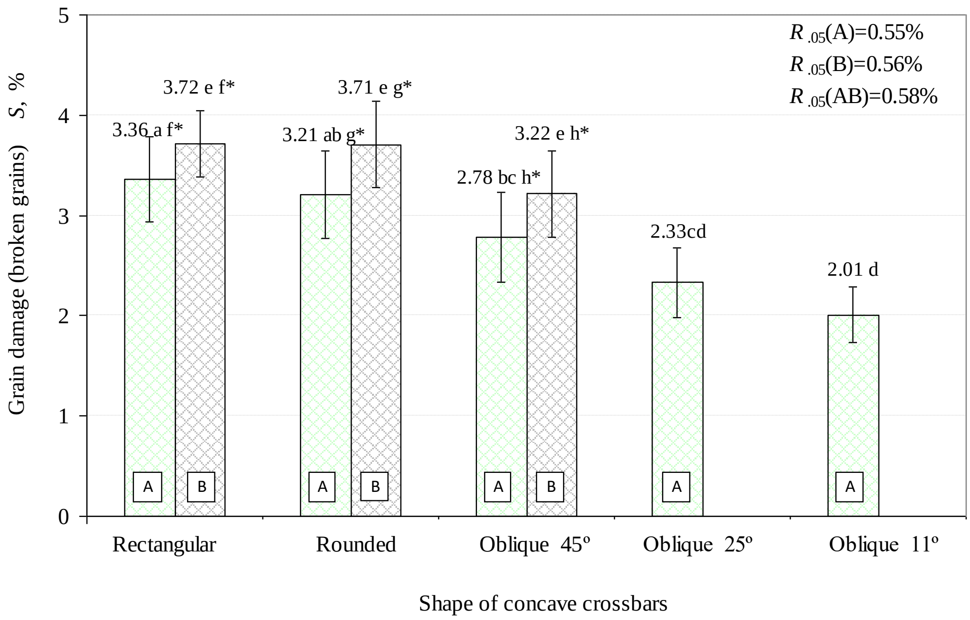


Figure 13. Influence of shape of concave crossbar working plane on total amount of damaged grain in threshing apparatus of combine harvester. A—experimental concave, B—control concave. a, b, c, d, e, f*, g*, h*—any two samples with a common letter are not significantly different ($p > 0.05$), as determined by one-way ANOVA (* is determined by two-way ANOVA).

Regardless of the shape of the working plane of the control and experimental concave crossbars, the damaged grain increased consistently toward the end of the threshing apparatus. The control concave had a slightly higher number of damaged grains, but the lowest confidence limits were not exceeded in any of the three compared cases (Figure 13). The reduction in damaged grain was attributed to the difference in the speed of movement of the corn ears, the number of interactions between the ears and rasp bars, and the consistency of the variation in the clearance between the cylinder rasp bars and crossbars of the concave. In the control concave, the clearance between the crossbars and the cylinder rasp bars increased at the beginning and then started to decrease, while in the experimental concave, the clearance between the crossbars and cylinder rasp bars decreased consistently over the length of the concave. Thus, the control threshing apparatus had twice as much interaction between the cylinder rasp bars and the ear compared to the experimental one.

The total amount of damaged grain using both rectangular and rounded crossbars exceeded the 3% limit. The results of the study show that the experimental concave with a 25° oblique working plane on the crossbars is the most effective one, as the grain damaged remains within the 3% permissible limit.

This confirms the results of previous studies, claiming that grain damage can be reduced if the harvested grain is passed through the grate of the concave as quickly as possible [7]. Furthermore, the threshing of the ear is more uniform with the use of crossbars with an oblique working plane. As the crossbars (25°) of such a working plane are wider (19 mm) than the rounded ones (8 mm), the ear rests on them over a larger area during impact. As the ear rotates at a greater angle during impact, the larger contact area ensures a more even impact and better separation of the grains from the cob.

4. Discussion

Several studies have been published in the scientific literature showing the impact of cylinder speed, concave clearance, ear feed rate, and ear moisture on the qualitative and quantitative parameters of corn ear threshing [7,15,47]. Combined harvester parameter settings of the cylinder speed, concave clearance, and feed rate are the primary factors that affect the harvester process parameters such as grain damage, threshing losses, and separation losses [8,32,48,49]. However, there is a lack of studies to evaluate the impact of working plane shape of concave crossbars on corn grain damage and separation through the concave's grate.

Aggressive threshing (e.g., increased cylinder speed, reduced concave clearance, etc.,) has been reported to reduce (or even avoid) threshing grain losses, while increasing grain damage [21]. The permissible limit for threshing losses in corn ears is 0.3% [21,22]. Threshing grain losses must be reduced by altering concave clearance [20]. According to numerous studies, grain moisture is the main factor affecting grain damage [7,50], but threshing grain with higher moisture content (above 35%) has been rarely investigated.

The present study demonstrates that the geometrical shape of the concave plane and its crossbars have a significant influence on the grain detachment from the ears, grain separation through the concave, and grain damage during the threshing process of moist ears of corn.

The diameters of the corn ears tend to decrease during threshing, and the clearance between the cylinder rasp bars and the concave crossbars likewise decreases along the length (Figure 1, sections I–III) of the concave. As the concave surface line of numerous combine harvesters corresponds to a circular arc, the reduction in clearance between the cylinder rasp bars and the concave crossbars is nonuniform along the concave length [50]. During cereal harvesting, the clearance between the cylinder rasp bars and concave crossbars is subject to variation within a narrow range [8], and nonuniform variation of this clearance insignificantly affects the qualitative performance indicators of threshing. In harvesting ears of corn, the clearance is approximately three-fold larger than that applied in cereal harvesting. A concave characterized by its surface line approximating Archimedes' spiral leads to a more uniform clearance variation [9,35]. Latest research [49] showed that the threshing gap of a corn combine harvester can be automatically controlled by gap adjustment in real-time, based on different feed rates to achieve adequate threshing efficiency and avoid excessive power consumption.

From the experiments in Section 3.1, it follows that independently of the control (the concave surface line corresponding to a circular arc) and the experimental (the surface line corresponding to an Archimedes' spiral) concave, the damaged grain by the shape of the working plane of the crossbars increased steadily toward the end of the threshing apparatus. Other researchers found similar trends [7,8,34].

The number of grains damaged was slightly higher in the threshing apparatus with a control concave, but the permissible limits were not exceeded in any of the three compared cases (Figure 13). The amount of damaged grain decreased due to differences in the speed of movement of the ears, the number of interactions between the ears and the rasp bars, and the consistency of the variation in the spacing between the cylinder rasp bars and concave crossbars. In the threshing apparatus with a control concave, the gap between the crossbars and rasp bars increased at the beginning and then started to decrease, while in the experimental concave, this gap decreased consistently over the length of the concave. Thus, the control threshing apparatus had twice as much interaction between the cylinder rasp bars and the ear as the experimental one. In our previous study [9], this hypothesis was proposed after analyzing the high-speed filming of the movement of corn ears on the surface of both concaves.

The total amount of damaged grain using both rectangular and rounded crossbars exceeded the permitted limit of 3%. Experimental findings supported the results of theoretical studies that the most effective design to thresh corn ears is a concave with crossbars with an oblique working plane [36]. The results of this study suggest that the most rational experimental approach is to use an experimental concave with an oblique working surface of 25°, as the amount of damaged grain is still within the permissible limit of 3%. This confirms the previous studies, which claimed that grain damage can be reduced if the harvested grain passes through the grate of the concave as quickly as possible [7]. One of the most important indicators of the threshing process of corn ears is the loss of grain separation, i.e., the grains that have been threshed, but have not been able to pass through the concave, i.e., grains that have fallen onto the straw walkers. To increase grain separation through the concave, the concave with the largest active separation area must be used [7]. Furthermore, the threshing of the ear is more uniform with the use of crossbars with an oblique working plane. As the crossbars (25°) of such a working plane are wider (19 mm) than the rounded ones (8 mm), such that the ear rests on them over a larger area during impact. The ear is rotated at a greater angle during impact. The larger contact area ensures a smoother impact on the ear, as demonstrated by the lower values of the power input coefficients of variation υ and the better separation of the grains from the kernel (Table 2).

The efficiency of corn ear threshing also can be evaluated by considering the power consumption [37]. Most research on threshing focused on reducing the power consumption for threshing wheat or rice, and there is a lack of research on the threshing efficiency of corn harvesters [49]. In the experimental concave of the present study, the use of crossbars with an oblique working plane (γ = 25°) resulted in a significantly higher uniformity of variation of the power demand at the steady-state (18.23 $\pm$ 0.23 kW) than the use of rectangular (16.91 $\pm$ 2.94 kW) or rounded crossbars (17.79 $\pm$ 1.75 kW).

To summarize our research, the concave design of the combine harvester is the most crucial prerequisite for the reduction of harvest losses due to grain damage. The shape of the arc of the concave working plane has an impact on the grain separation and its losses in the threshing apparatus i.e., the grain that falls on the straw walkers. The experimental concave can on average double the separation of the grain threshed through the concave's edges. In the experimental concave, it is advisable to employ crossbars with an oblique working plane and a tilt angle of γ = 25°.

5. Conclusions

Experimental studies show that replacing the concave rounded crossbars with oblique ones can increase the grain separation through the concave, reduce the grain falling on the straw walkers and the amount of damaged grain, and help avoid threshing grain losses, i.e., increase threshing performance of moist corn ears.

Studies show that the geometrical shape of the concave arc and its crossbars have a significant impact on quality of corn ear threshing.

The most rational way of threshing moist corn ears is to use an experimental concave with an Archimedes' spiral arc and an 8 mm high, 19 mm wide crossbars of the concave with an oblique working plane (tilt angle 25°). The grain losses when threshing moist ears (grain moisture content ~35%) is then minimal (0.03% $\pm$ 0.02%), and the portion of grain damaged in the threshing apparatus does not exceed the permitted limit of 3%, at a corn ear feed rate of 16.8 kg s^{-1}.

In terms of the power requirement for threshing, the shape of the working plane of the experimental concave results in a power consumption that is about 2 kW higher than that of the control. The experimental concave has a smoother threshing action with the use of crossbars on the oblique concave surface. This is likely to have a positive effect on the driving elements of the threshing cylinder.

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