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Enhancing the Performance of Sunflower Threshing Machines through Innovative Enhancements

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Abstract: Improving the performance of the threshing process is of utmost importance in enhancing the quality of sunflower seeds and minimizing power consumption in sunflower production. In this study, we developed a modified sunflower threshing machine by incorporating two types of threshing rotors, namely the angled rasp bar rotor and the tine bar rotor, as compared to the round bar rotor. The performance of these rotors was evaluated under various rotational speeds (150, 200, 250, and 300 rpm) and concave clearances (10, 15, and 20 mm). The evaluation parameters included machine throughput, the specific energy of threshing, the percentage of damaged seeds, the percentage of unthreshed seeds, and threshing efficiency. The results indicate that the specific energy decreased with an increase in rotor speed and a decrease in concave clearance, with the tine bar rotor exhibiting the lowest values. Threshing efficiency showed an increasing trend with higher rotor speeds and reduced concave clearance. The modifications made to the rotor design resulted in an enhanced threshing efficiency, with an improvement from 96.30% to 97.93% achieved at a rotor revolving speed of 300 rpm and a concave clearance of 10 mm. Moreover, the specific energy consumption reduced from 9.65 kW·h/ton to 5.09 kW·h/ton under the same operational conditions. These findings highlight the efficacy of the novel rotor design modifications in optimizing the performance of the stationary sunflower threshing machine, leading to improved efficiency and reduced energy consumption in sunflower seed threshing operations. Given its performance characteristics, this machine exhibits potential suitability for sunflower farms of small to medium scale.

Keywords: sunflower thresher; development; machine performance; optimization

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1. Introduction

Sunflower (*Helianthus annuus* L.) is recognized as one of the key oilseed crops globally. The global demand for edible oils amounts to approximately 85 million tons, with herbal oils constituting roughly 75% of this consumption, while animal oils account for the remaining 25% [1]. Sunflower possesses a notable oil content of 40%, surpassing that of any other oilseed crop [2]. Sunflower oil is considered one of the most important globally produced herbal crude oils [3]. China achieved the status of being the fifth-largest global producer of sunflower seeds in 2018, with an annual production volume of 2.55 million tons [4].

Farmers operating on small and medium areas use traditional methods in threshing sunflower crops. This method primarily involves the application of force to the heads of crops using various implements, such as metal pieces, stones, or wood, either through striking or rubbing actions. These actions are performed after the cutting and drying processes. Overall, the efficiency of this method is considerably low due to its reliance on the skill and performance of farmers [5,6]. Post-harvest and processing operations account for over 40% of the total losses incurred [7]. Furthermore, the effectiveness of traditional manual techniques is dependent on the proficiency of operators, thereby limiting their overall efficacy [8]. This method is significantly influenced by environmental factors, resulting in the production of low-quality products due to the presence of impurities such as stones, dust, and chaff. Additionally, losses occur due to seed breakage or burial in the soil. The principal drawback of this method is its high level of consumption of energy and time.

The operational efficacy of the threshing module in an impact thresher is pivotal in determining the rate at which kernels are harvested in grain production [9,10]. The kernel harvest rate refers to the speed at which intact kernels are acquired during the threshing process [11]. Presently, the most prevalent threshing component employed is the rigid threshing component (RTC), which relies on a rigid impact to promptly dislodge the kernels [12,13]. The higher the impact force exerted by the RTC on the kernels, the greater the threshing rate, but also the higher the rate of kernel damage [14]. Bionic mechanism design has been extensively validated as an effective approach for enhancing the performance of agricultural components [15]. In contrast, manual threshing operations exhibit negligible kernel damage, thus yielding exceedingly high cleanliness [16].

Threshing platforms can be evaluated based on several parameters, including machine output, power consumption, threshing efficiency, grain damage, and unthreshed grain. Studies have investigated the influence of variables such as rotor speed, feed rate, and moisture content on thresher performance, separation efficiency, and seed losses. This process can be accomplished through the implementation of various actions, either individually or in combination. These actions may include the application of impact by a high-speed member on the material, the rubbing and squeezing of pods, and other related techniques [17].

The optimal configuration of a sunflower threshing apparatus and its efficacy can be determined based on parameters such as machine output, power consumption, threshing efficiency, grain damage, and unthreshed grain utilizing rudimentary tools and human labor (manual approach), as well as through the utilization of an advanced mechanized threshing machine (mechanical method) [18,19]. These evaluation parameters were followed in the current work to judge the performance of the threshing platform. The authors of [20] studied the effect of rotor speed, feed rate, and moisture content on the output of the thresher, threshing efficiency, separation efficiency, the percentage of seed losses, and damaged seeds for a sunflower-developed thresher machine. The authors of [21] designed a device for threshing sunflowers and tested the effect of rotor threshing type, rotor rotational speed, and feeding rate on the performance of the device; their results revealed that for the separation rate, the optimal operational condition is a ribbed-rod cylinder, with a 430 rpm cylinder rotational speed, and a 8820 kg/h feeding quantity, while the optimal combination for the breakage rate is an arch-tooth cylinder with a 280 rpm cylinder rotational speed and a feeding quantity of 8820 kg/h.

Stationary threshing machines are more convenient for threshing and separating seeds from their heads [22]. These machines have high efficiency and ensure slight losses of seeds with suitable throughput, which means that these machines are particularly well-suited for farmers with small and medium-area holdings. In addition, stationary threshing machines can be used as an experimental prototype to develop harvesting combines [23]. The cost of acquiring and deploying the threshing machine may be a significant consideration for farmers, especially those with limited financial resources. Additionally, the maintenance and repair of the machine may require specialized skills and spare parts, which could pose challenges in regions with limited access to technical support.

This study aims to enhance sunflower production, minimize power and labor requirements, and enhance the quality of sunflower seeds. To achieve these objectives, it is imperative to improve, test, and evaluate a sunflower threshing machine. Consequently, a stationary sunflower thresher machine was developed, incorporating the design of two open-system threshing rotors, namely the angled rasp bar rotor and the tine bar rotor, for comparison with the closed round bar rotor. These rotors were subjected to testing under varying rotational speeds of 150, 200, 250, and 300 rpm while employing different concave clearances of 10, 15, and 20 mm.

2. Materials and Methods

The current investigation was conducted in Taizi Town, Huangshi City, Hubei, China, focusing on the DW667 cultivar of *Helianthus annuus* oilseeds harvested through manual means at a moisture content of 16.75% (w/w). This investigation was predicated upon the concept of maximizing the depth of penetration of the threshing implement within the sunflower capitulum in order to augment the efficacy of the threshing apparatus and curtail the energy expenditure during the threshing operation by diminishing the interfacial friction between the active component and sunflower head. Consequently, the energy was concentrated on the seed extraction from the sunflower head.

2.1. Machine Contents and Modifications

To effectively thresh and separate oilseed sunflowers, a longitudinal axial flow thresher was employed to perform the crucial tasks of seed removal from sunflower heads and seed cleaning, specifically removing non-grain material. The thresher and separator constitute the two essential components of this machine. The machine frame's dimensions are as follows: length, 1700 mm; width, 1300 mm; and height, 1100 mm. Figure 1 illustrates the axial flow sunflower threshing machine utilized in this study.

The threshing unit encompasses a one-cylinder, axial-flow thresher with a length of 1040 mm and a diameter of 200 mm for each threshing rotor. Two types of threshing rotors were employed, including the round bar rotor, from which the design was developed. Figure 2 showcases a SolidWorks 2023 model and a photograph of the prototype for both the round bar and newly designed rotors, which possess the following specifications:

Round bar: This rotor features a closed threshing design with a circular section bar of 20 mm diameter.

Angled rasp and tine bars (newly designed bars): These rotors have an open-threshing design. The bars of these rotors are arranged in three sections, each with a width of 30 mm and a thickness of 10 mm. There are 41 teeth on each bar, with a distance of 15 mm between consecutive teeth. The teeth protrude 20 mm above the diameter of the threshing rotor. In the case of the angled rasp bar, the teeth are inclined at a 45-degree angle relative to the longitudinal axis of the bar. On the other hand, the teeth of the tine bar are perpendicular to the longitudinal axis.

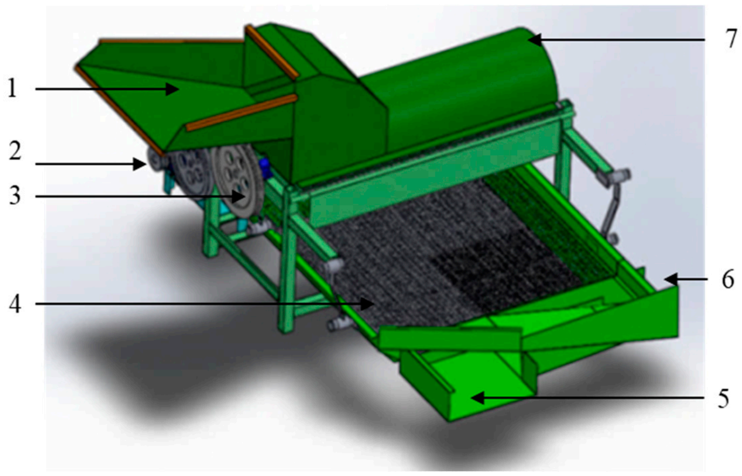

Figure 1. A 3D model for the stationary sunflower threshing machine. (1) Feeder; (2) power source; (3) power transmission; (4) separating unit; (5) seed's outlet; (6) straw outlet; (7) thresher cover.

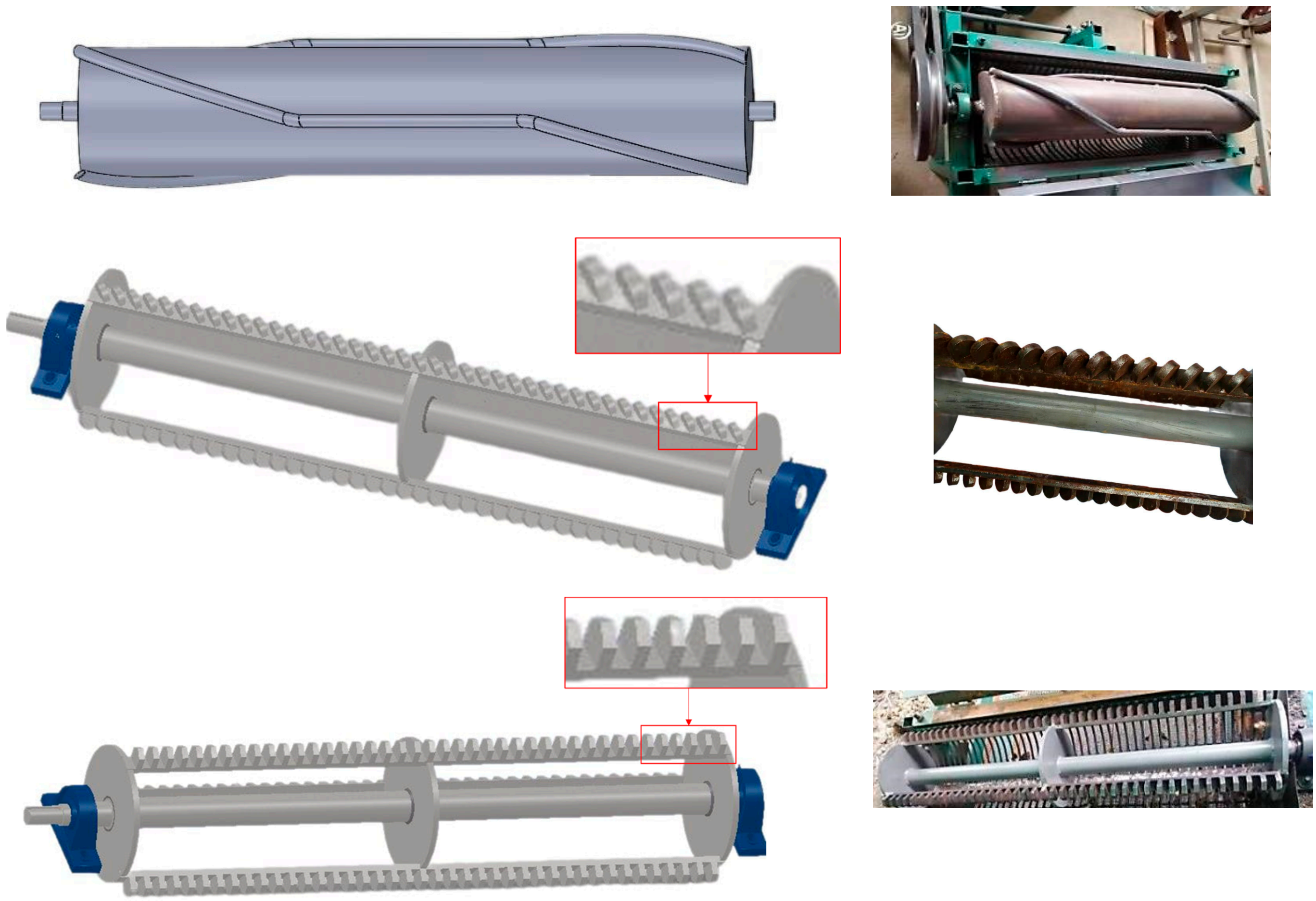

Figure 2. Schematics (right) and photos (left) of the round bar (top), angled rasp bar (middle), and tine bar (bottom) rotors.

The decision to use three threshing bars was made based on the specific experimental setup and objectives of the current investigation. By using this low number of threshing bars, the investigation aimed to isolate and analyze the impact of these elements on threshing efficiency, specific consumed energy, and seed loss.

The mainframe, constructed from iron angles and boxes with dimensions of 45 mm × 45 mm × 3 mm, supports the threshing unit, separating unit, power source, and power transmission system.

2.2. Software Programs

The design and endurance testing of the new threshing bars (angled rasp bar and tine bar) were conducted using SolidWorks 2016 software, taking into consideration the specific physical and mechanical properties of the sunflower variety. Additionally, the impact of the study parameters on the performance of the threshing machine was examined using SPSS 20 software. The analysis involved employing a two-way analysis of variance (ANOVA) method, followed by the least significant difference (L.S.D.) test ($p < 0.05$). The randomized complete block design was utilized for the experimental setup and data analysis.

2.3. Experimental Design

The performance of the sunflower stationary threshing machine was assessed by analyzing its response to various threshing rotor types, namely the round bar rotor, angled rasp bar rotor, and tine bar rotor. Additionally, the machine's performance was evaluated at different rotor rotational speeds, including levels of 150, 200, 250, and 300 rpm (corresponding to linear velocities of 1.73, 2.30, 2.88, and 3.46 m/s). Moreover, the effect of concave clearance, with distances of 10, 15, and 20 mm, on machine performance was investigated. The experimental design employed was a randomized complete block design with a 3 × 4 × 3 factorial arrangement, with three replications for each treatment. To compare treatment means, the least significant difference (L.S.D) test at a 5% significance level was applied, following the methods described by [24,25]. Each replicate of the experiment utilized 10 kg of sunflower heads.

2.4. Measurements

Machine throughput

The machine throughput was calculated by dividing the quantity of threshed sunflower heads by the threshing time, as per the following equation:

$$\text{Thresher throughput}(t/h) = \frac{S_w \times 3600}{1000 \times T} \tag{1}$$

where S_w is the quantity of threshed material on a wet basis (kg) and T is the threshing time (seconds).

The specific energy

The specific energy (kW.h/ton) was considered by dividing the consumed power (kW) by machine output throughput (ton/h).

The percentage of unthreshed seed

The percentage of unthreshed seed was calculated with the following equation [26].

$$\mathrm{Ut_l} = \frac{\mathrm{Ut}_m}{\mathrm{Ut}_m + \mathrm{S}_{outlet} + dameged\ seed} \times 100 \tag{2}$$

where $\mathrm{Ut_l}$ is the unthreshed seed percentage (%), Ut_m is the unthreshed seed mass (g), and S_{outlet} is the threshed seed mass (g).

The seed damaged percentage

The seed damaged percentage was measured using the following equation

$$\text{Seed damage percentage}(\%) = \frac{d}{t} \times 100 \tag{3}$$

where d is the amount of seed damage (g) and t is the total mass of the sample (g).

Threshing efficiency

The threshing efficiency% was calculated from the following expression [26].

Threshing efficiency% = 100—total losses percentage (unthreshed seeds + damage seeds).

3. Results and Discussions

3.1. Statistical Analysis

Table 1 displays the analysis of variance conducted to evaluate the significance of the study parameters (rotor type A, clearance B, and rotor speed C), as well as their interaction, with respect to the performance of the sunflower threshing machine (throughput, specific energy, damaged seed, unthreshed seed, threshing efficiency).

Table 1. Analysis of variance table for main treatments and interactions.

Source of Variation	df	F Value				
		Throughput	**Specific Energy**	**Damaged Seed**	**Unthreshed Seed**	**Threshing Efficiency**
Rotor type A	2	369.07 **	691.61 **	335.20 **	1844.66 **	1144.17 **
Clearance B	2	163.54 **	0.67 ^{ns}	168.62 **	312.94 **	143.66 **
Rotor speed C	3	372.40 **	26.46 **	298.67 **	856.66 **	453.12 **
A × B	4	1.98 ^{ns}	0.89 ^{ns}	1.67 ^{ns}	1.82 ^{ns}	2.34 ^{ns}
A × C	6	6.60 **	2.35 *	1.74 ^{ns}	15.90 **	11.16 **
B × C	6	10.35 **	2.02 ^{ns}	6.05 **	1.07 ^{ns}	2.64 *
A × B × C	12	0.50 ^{ns}	0.58 ^{ns}	0.40 ^{ns}	3.97 **	3.46 **
Error	72					

** Significant at 1%. * Significant at 5%. ^{ns}, non-significant.

3.2. The Machine Throughput

In general, machine throughput was significantly influenced by all variables examined in this study. Across all types of threshing rotors, the machine throughput demonstrated an increase with the rise in rotor rotational speed, consistent with the findings from [20,27] within the same range of feed rate and linear speed. In contrast, machine throughput decreased with increasing concave clearance (Figure 3). This decline in throughput at high concave clearances may be attributed to the longer residence time of sunflower heads within the threshing area.

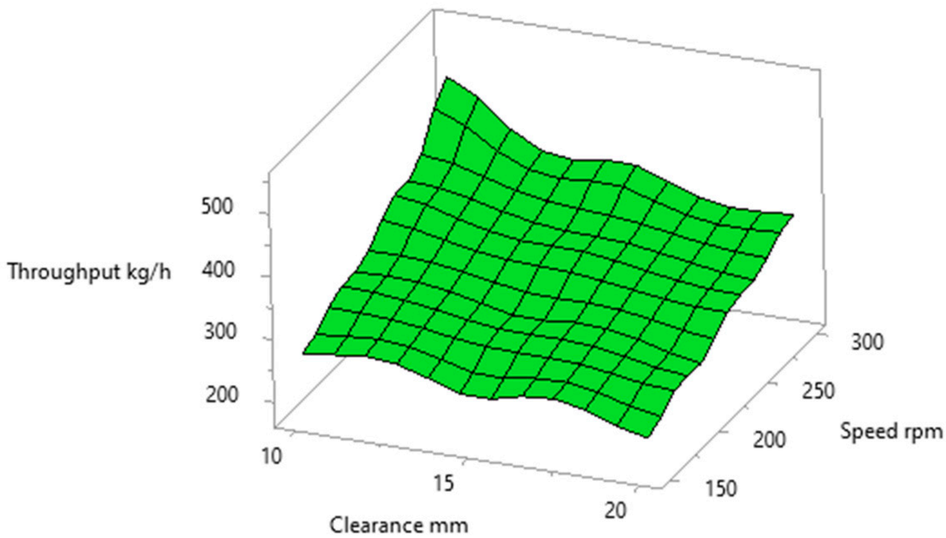

Figure 3. Machine throughput (kg/h) vs. different clearances (mm) and different speeds (rpm).

Notably, the angled rasp bar rotor consistently yielded higher machine throughput values compared to the other rotor types under all operational conditions. Maybe the efficient arrangement of teeth at a 45-degree angle facilitated the swift passage of sunflower heads through the threshing chamber, resulting in enhanced throughput. This ensures the optimal utilization of the rotor length, resulting in improved machine throughput (see Figure 4). The highest machine output value of 506.6 kg/h was recorded at a rotor rotational speed of 300 rpm and a concave clearance of 10 mm using the angled rasp bar rotor.

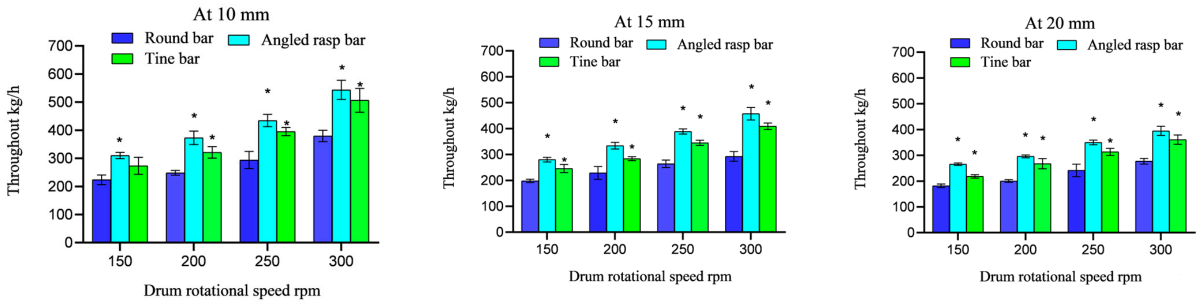

Figure 4. Effect of rotor speed (rpm) and rotor type on machine throughput (kg/h) at different concave clearances (mm). The data shown are averages of three replicates ± SD. Asterisks indicate significant differences from the round bar rotor at 5%.

3.3. Threshing Specific Energy

The consumed specific energy of the machine was determined by considering its throughput and power requirements during calculation. As depicted in Figures 5 and 6, the consumed specific energy exhibited a decrease with increasing rotor speed. In particular, the consumed specific energy values for the round bar rotor were higher compared to the regression values for the angled rasp bar and tine bar rotors. This discrepancy may be attributed to variations in the rotor body design, where the open rotor design of the angled rasp bar and tine bar rotors resulted in a reduction in non-essential friction between the rotor body and the sunflower heads. The decrease in consumed specific energy with increasing the rotor's rotational speed can be attributed to the dominant influence of enhanced machine throughput (denominator) rather than the corresponding increase in power requirements (numerator). This result agrees with [28,29].

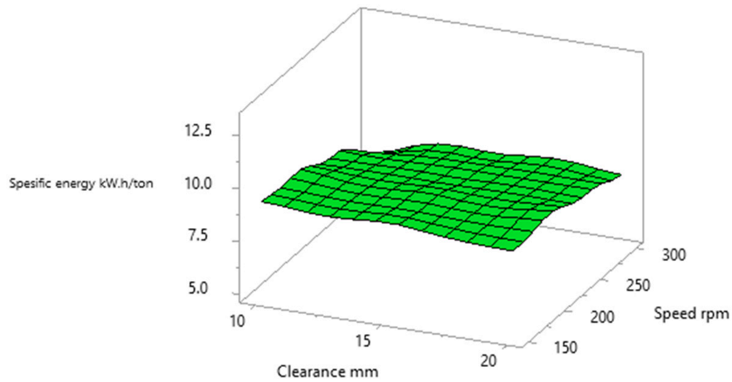

Figure 5. Consumed specific energy (kW.h/ton) vs. different clearances (mm) and different speeds (rpm).

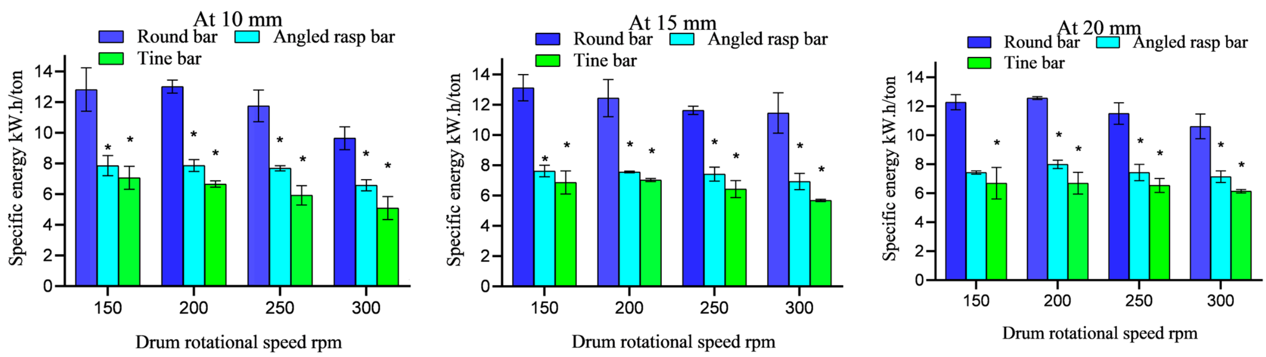

Figure 6. Effect of rotor speed (rpm) and rotor type on specific energy (kW.h/ton) at different concave clearances (mm). The data shown are averages of three replicates ± SD. Asterisks indicate significant differences from the round bar rotor at 5%.

3.4. The Seed Damage Percentage

Figures 7 and 8 elucidate that the percentage of damaged seeds exhibited an increase with rising rotor rotational speed, a finding consistent with studies by [20,27]. On the other hand, the damaged seed percentage decreased with increasing concave clearance across all rotor types. In particular, the round bar rotor consistently yielded lower values of damaged seed percentage compared to the angled rasp bar and tine bar rotors at various rotor rotational speeds and concave clearances. The minimum damaged seed value of 0.27% was obtained using the round bar rotor at a rotor speed of 150 rpm and a concave clearance of 20 mm. In contrast, the highest damaged seed value of 1.47% was recorded at a rotor speed of 300 rpm and a concave clearance of 10 mm for the angled rasp bar rotor.

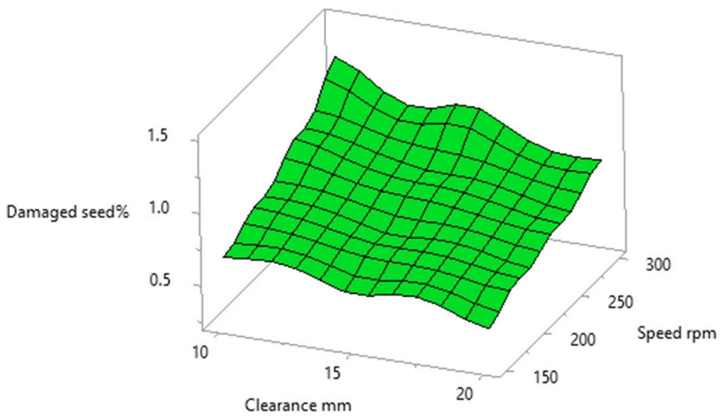

Figure 7. Damaged seed % vs. different clearances (mm) and different speeds (rpm).

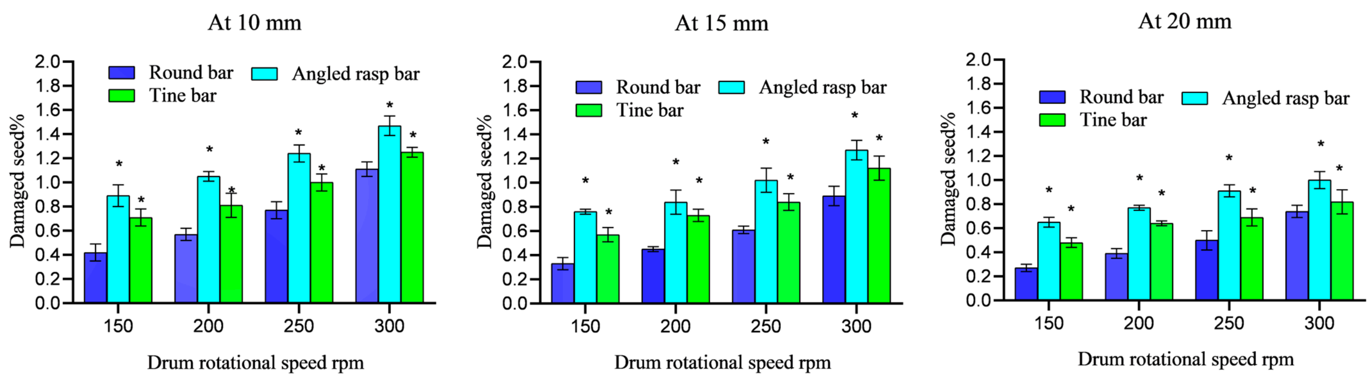

Figure 8. Effect of rotor speed (rpm) and rotor type on damage seed percentage (%) at different concave clearances (mm). The data shown are averages of three replicates ± SD. Asterisks indicate significant differences from the round bar rotor at 5%.

The relatively low percentage of broken grains observed with the round bar rotor can be attributed to the circular cross-section of the bar, resulting in less friction compared to the other two bars.

The increase in damaged seed percentage at high rotor rotational speeds and low concave clearances may be attributed to the heightened impact speed and energy between the sunflower heads and the rotor, as well as the concave body. The observed rise in the proportion of unthreshed seeds within the tine bar rotor, as opposed to the angled rasp bar rotor, can plausibly be attributed to the small surface area of contact between the threshing teeth and sunflower heads within the tine bar rotor, in comparison to the angled rasp bar rotor.

3.5. Fraction of Unthreshed Seed

Figures 9 and 10 exhibit a consistent trend across all rotor types, whereby the percentage of unthreshed seeds decreased with increasing rotor rotational speed and decreasing concave clearance, aligning with the findings of [30]. Markedly, the angled rasp bar rotor consistently exhibited a lower percentage of unthreshed seeds compared to the other two rotor types across all operational conditions. The minimum value of unthreshed seeds, 0.71%, was achieved at a rotor rotational speed of 300 rpm and a concave clearance of 10 mm for the angled rasp bar rotor, while the maximum value of 7.13% was recorded at a rotor rotational speed of 150 rpm and a concave clearance of 20 mm for the round bar rotor.

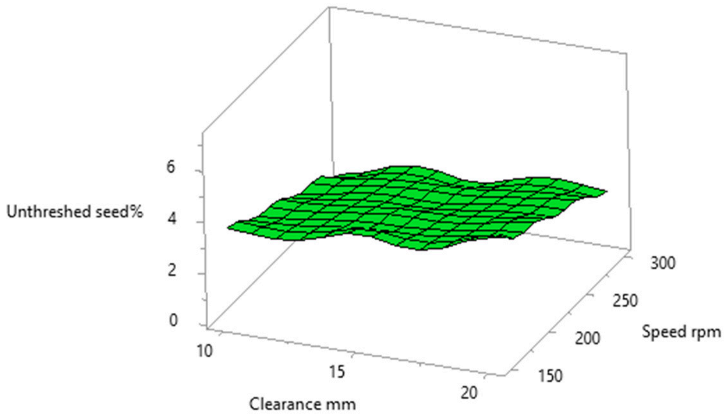

Figure 9. Unthreshed seed % vs. different clearances (mm) and different speeds (rpm).

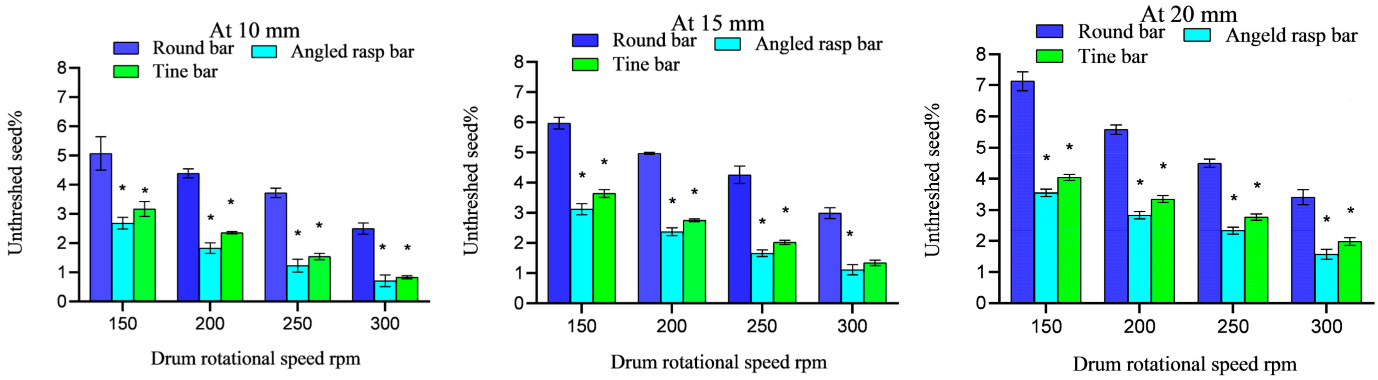

Figure 10. Effect of rotor speed (rpm) and rotor type on unthreshed seed percentage (%) at different concave clearances (mm). The data shown are averages of three replicates $\pm$ SD. Asterisks indicate significant differences from the round bar rotor at 5%.

The presence of interspaces on both the angled rasp bar rotor and tine bar rotor facilitated the penetration of the bars' teeth into the sunflower heads, resulting in a reduction in the percentage of unthreshed seeds compared to the round bar rotor. The observed rise in the proportion of unthreshed seeds within the tine bar rotor, as opposed to the angled rasp bar rotor, can plausibly be attributed to the small surface area of contact between the milling teeth and sunflower heads within the tine bar rotor in comparison to the angled rasp bar rotor.

3.6. Threshing Efficiency

Figures 11 and 12 demonstrate the positive correlation between rotor rotational speed and threshing efficiency while revealing an inverse relationship between concave clearance and threshing efficiency across all rotor types. Prominently, the threshing efficiency values of the angled rasp bar rotor generally surpassed those of the tine bar and round bar rotors, except for a single operational condition. Comparatively, the tine bar rotor exhibited slightly superior threshing efficiency when compared to the angled rasp bar rotor. Significantly, at high rotor rotational speeds and small concave clearances, the threshing efficiency values of the tine bar and angled rasp bar rotors were closely aligned. The maximum threshing efficiency value of 97.93% was attained at a rotor rotational speed of 300 rpm and a concave clearance of 10 mm for the tine bar rotor.

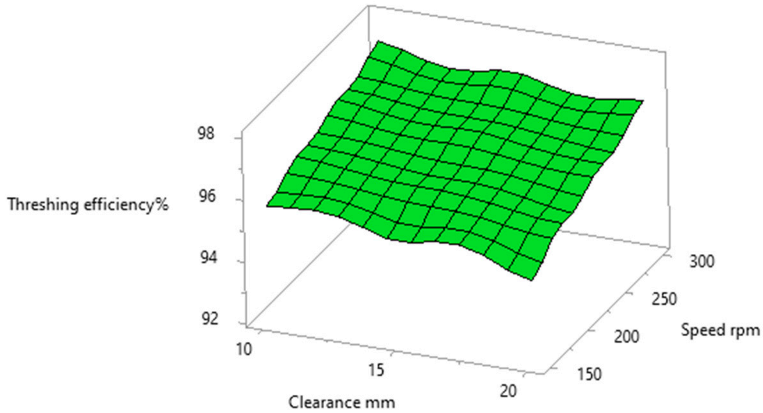

Figure 11. Threshing efficiency % vs. different clearances (mm) and different speeds (rpm).

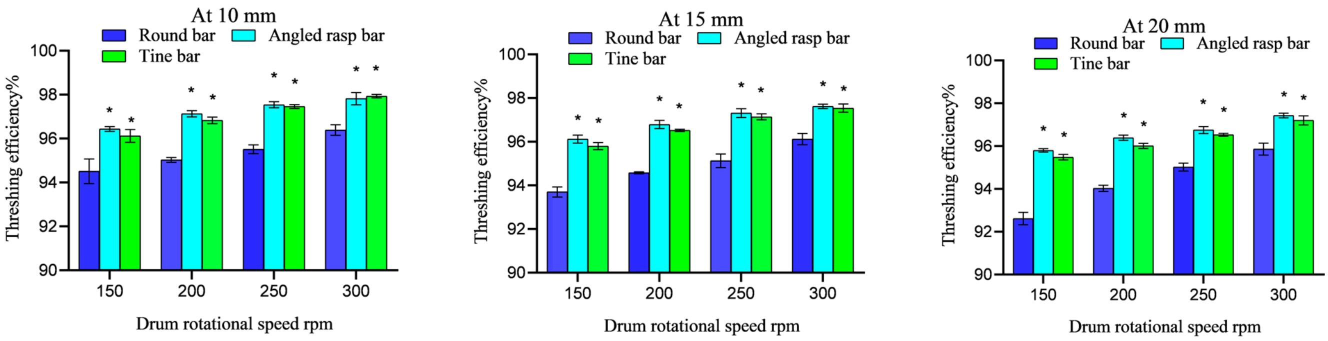

Figure 12. Effect of rotor speed (rpm) and rotor type on the threshing efficiency (%) at different concave clearances (mm). The data shown are averages of three replicates ± SD. Asterisks indicate significant differences from the round bar rotor at 5%.

The lowest values of unthreshed seeds were recorded at high rotor rotational speeds and low concave clearance values. On the other hand, the percentage of damaged seeds exhibited an opposite trend under the same operational conditions. It is noteworthy that the presence of unthreshed seeds had a more significant impact on threshing efficiency compared to the percentage of damaged seeds, as higher seed quantities and lower concave clearances contributed to an increase in threshing efficiency.

4. Conclusions

The threshing process plays a crucial role in assessing product quality, and the utilization of threshing equipment offers significant benefits in terms of enhanced product quality, reduced processing time, and minimized labor requirements. The modifications implemented on the round rotor (original rotor) resulted in an augmentation of the threshing efficiency by enhancing the penetration of the active components of the sunflower heads by means of the teeth. Consequently, this led to a higher percentage of seed extraction from the heads. Additionally, the newly designed open rotors (angled rasp bar and tine bar) contributed to a reduction in the specific energy required for the threshing process.

The authors express their intention to carry out a simulation utilizing simulation programs to forecast the efficiency of the thresher. Furthermore, we plan to incorporate pressure sensors between the thresher rotor and the concave. This will enable the transmission of a signal to the automatic feeder unit, which will be integrated as part of the modifications. The purpose of this integration is to regulate the feed rate.

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References

1. Aysu, A. Sunflower farming in Turkey. *Türkiye'de Ayçiçegi Tarımı*. 2017. Available online: http://www.karasaban.net/aycicegi-bitkisel-yag/ (accessed on 25 June 2017).
2. Amjad, N.; Shaheen, M.A. Comparative performance of different threshing drums for sunflower. *Agric. Mech. Asia Afr. Lat. Am.* **1993**, *24*, 23.
3. El-Hamidi, M.; Zaher, F.A. Production of vegetable oils in the world and in Egypt: An overview. *Bull. Natl. Res. Cent.* **2018**, *42*, 19. [CrossRef]
4. FAO (Food and Agriculture Organization). Available online: https://www.fao.org/faostat/ar/#data/QC (accessed on 23 July 2020).
5. Goel, A.K.; Behera, D.; Swain, S.; Behera, B.K. Performance evaluation of a low-cost manual sunflower thresher. *Indian J. Agric. Res.* **2009**, *43*, 37–41.
6. Mirzabe, A.H.; Khazaei, J.; Chegini, G.R. Physical properties and modeling for sunflower seeds. *Agric. Eng. Int. CIGR J.* **2012**, *14*, 190–202.
7. Gustavsson, J.; Cederberg, C.; Sonesson, U.; Van Otterdijk, R.; Meybeck, A. *Global Food Losses and Food Waste*; FAO: Rome, Italy, 2011.
8. Azharuddin, K.; Mir, S.; Narasimhan, M.M.; Kumar, G.P. Design and fabrication of sunflower seed extracting machine. *Int. J. Latest Technol. Eng. Manag. Appl. Sci.* **2016**, *5*, 90–97.
9. Fu, J.; Chen, Z.; Han, L.; Ren, L. Review of grain threshing theory and technology. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 12–20. [CrossRef]
10. Pakhomov, V.I.; Braginets, S.V.; Bakhchevnikov, O.N.; Benova, E.V.; Rukhlyada, A.I. Experimental data of the ear threshing process in a pneumatic device. *Eng. Technol. Syst.* **2020**, *30*, 111–132. [CrossRef]
11. Yang, R.; Chen, D.; Zha, X.; Pan, Z.; Shang, S. Optimization design and experiment of ear-picking and threshing devices of corn plot kernel harvester. *Agriculture* **2021**, *11*, 904. [CrossRef]
12. Fisunova, E.; Lavrenova, T.; Zharov, V. Using the imitation model of elementary technological operation at the evaluation of the threshing action of the threshing device. In Proceedings of the MATEC Web of Conferences, Bojnice, Slovakia, 11–13 September 2018; p. 5018.
13. Qian, Z.; Jin, C.; Zhang, D. Multiple frictional impact dynamics of threshing process between flexible tooth and grain kernel. *Comput. Electron. Agric.* **2017**, *141*, 276–285. [CrossRef]
14. Ren, H.; Tang, Z.; Li, X.; Li, Y.; Liu, X.; Zhang, B.; Li, Y. Method for measuring rice grain internal damage degree undergoing threshing force. *Int. J. Agric. Biol. Eng.* **2021**, *14*, 63–73. [CrossRef]
15. Zhou, K.D.; Wang, J.G.; Li, J.M.; Liao, J.M. Dynamic Analysis and Simulation for Bionic Power-Assisted Legs of Hill Area Agricultural Machinery. *Adv. Mater. Res.* **2013**, *675*, 107–110. [CrossRef]
16. Fu, J.; Yuan, H.; Zhang, D.; Chen, Z.; Ren, L. Multi-objective optimization of process parameters of longitudinal axial threshing cylinder for frozen corn using RSM and NSGA-II. *Appl. Sci.* **2020**, *10*, 1646. [CrossRef]
17. Kepner, R.A.; Bainer, R.; Barger, E.L. *Principles of Farm Machinery*, 3rd ed.; AVI Publishing Co., Inc.: Westport, CT, USA, 1978.
18. Gregory, J.M.; Fedler, C.B. Model evaluation and research verification (MERV). *Am. Soc. Agric. Eng.* **1986**. Paper No. 86-5032.
19. Ndirika, V.I.O. Modeling the Performance of Selected Stationary Grain Threshers. Ph.D. Thesis, The Agricultural Engineering Department at Ahmadu Bello University, Zaria, Nigeria, 1997.
20. Abdollahpour, S.; Ghassemzadeh, H. Designing, fabrication and evaluation of threshing unit edible sunflower. *Agric. Eng. Int. CIGR J.* **2019**, *21*, 52–58.
21. Li, X.; Zhang, X.; Zhu, X. Design and experimental study on threshing device of oil sunflower combine harvester. *J. Chin. Agric. Mech.* **2019**, *40*, 6–12.

22. Ali, K.A.M.; Zong, W.Y.; Ma, L.N.; Abd El-Wahhab, G.G.; Li, M. Testing, Evaluating and Simulate the Performance of the Newly Designed Drum for a Sunflower Threshing Machine. *Int. J. Eng. Res. Afr.* **2022**, *60*, 29–41. [CrossRef]
23. Ovchinnikov, A.S.; Lovchikov, A.P.; Ryadnov, A.I.; Fedorova, O.A.; Konstantinov, M.M.; Fomin, S.D. On the substantiation of the technological scheme of the combine harvester with the stationary process of threshing bread mass. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Stavropol, Russia, 21–22 October 2019; p. 12057.
24. Box, G.E.; Hunter, W.H.; Hunter, S. *Statistics for Experimenters*; John Wiley and Sons: New York, NY, USA, 1978; Volume 664.
25. Gomez, K.A.; Gomez, A.A. *Statistical Procedures for Agricultural Research*; John Wiley & Sons: New York, NY, USA, 1984.
26. Ismail, Z.E.; Elhenaway, M.N. Optimization of machine parameters for a sunflower thresher using friction drum. *J. Agric. Sci. Mansoura Univ.* **2009**, *34*, 10293–10304.
27. Sudajan, S.; Salokhe, V.M.; Triratanasirichai, K. PM—Power and machinery: Effect of type of drum, drum speed and feed rate on sunflower threshing. *Biosyst. Eng.* **2002**, *83*, 413–421. [CrossRef]
28. El Ghobashy, H.; Shaban, Y.; Okasha, M.; Abd El-Reheem, S.; Abdelgawad, M.; Ibrahim, R.; Ibrahim, H.; Abdelmohsen, K.; Awad, M.; Cottb, M.; et al. Development and evaluation of a dual-purpose machine for chopping and crushing forage crops. *Heliyon* **2023**, *9*, e15460. [CrossRef]
29. Ahmed, R.A.A. Evaluation of local machine performance for faba bean curshing. *Misr. J. Agric. Eng.* **2017**, *34*, 1167–1178. [CrossRef]
30. Ali, K.A.M.; Zong, W.; Md-Tahir, H.; Ma, L.; Yang, L. Design, Simulation and Experimentation of an Axial Flow Sunflower-Threshing Machine with an Attached Screw Conveyor. *Appl. Sci.* **2021**, *11*, 6312. [CrossRef]