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# A Study of the Distribution of the Threshed Mixture by a Double Longitudinal Axial Flow Corn Threshing Device

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**Abstract:** In order to determine the distribution pattern of the threshed mixture in the double longitudinal axial flow threshing device, single-factor experiments were conducted on the self-developed experimental platform for the double longitudinal axis threshing device. The experimental factors included drum speed, threshing clearance, and feed rate. The variations in the distribution of the threshed material along the axial and radial directions were examined. The results indicate that the mixed material after threshing exhibits uneven distribution both axially and radially. Along the axial direction, the mass of corn kernels initially increases and then decreases and is predominantly distributed in the front one-third section of the drum. Meanwhile, the mass of corn cobs continuously increases. In the radial direction, the mass of corn kernels and cobs is higher in the middle and on both sides, with the corn kernels being most concentrated in the middle and the corn cobs mostly on the sides. Combining the corn kernel breakage rate and the unthreshed rate, the optimal operating conditions were determined as follows: a drum speed of 400 r/min, a concave clearance of 50 mm, and a feed rate of 16 kg/s.

**Keywords:** double longitudinal axis threshing device; threshed mixture distribution; cleaning system

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## 1. Introduction

As the planting area of grain crops continues to expand in China, it has driven the development of combine harvesters toward larger feeding capacities and higher efficiency [1,2]. Drawing on the development experience of combine harvesters abroad, the double longitudinal axis threshing device plays a crucial role in addressing the challenges of harvesting grains with large feeding capacities. This device not only leverages the gentle nature of longitudinal axis threshing and its good adaptability to crops but also meets the requirements of high-feeding threshing [3,4]. Based on the mechanism of longitudinal axis threshing, when the harvested grain mixture falls onto the cleaning sieve through the concave plate, its distribution significantly impacts the cleaning system, especially in cases of larger feeding capacities, where it may lead to local accumulation and, consequently, affect the distribution of airflow, resulting in high impurities and losses [5–8]. Therefore, conducting research on the distribution of the threshed mixture on the cleaning sieve of the double longitudinal axis threshing device holds significant practical importance for optimizing the fan structure and improving the operational performance of harvesters.

In recent years, scholars both domestically and internationally have conducted extensive theoretical and experimental research on the distribution patterns of post-threshing mixtures. Miu et al. [9–12] studied the threshing separation process of a rod tooth axial flow threshing device derived the separation rate theory of grains and impurities and the separation model with a change in drum length, which were verified by experiments. Valentin et al. [13] used a threshing device to establish a threshing separation model and studied the radial distribution pattern of the threshing device. They analyzed the impact

of structural parameters and operating parameters on threshing performance, deriving a regression equation for radial distribution. Kumar et al. [14,15] calculated and analyzed the force exerted on crops during the threshing process. They derived a set of differential equations describing the threshing separation process in a combine harvester, indicating that the probability distribution of grain separation in the threshing space follows an exponential decay function of threshing time. Badretdinov et al. [16] simulated and analyzed the cleaning process of grain combine harvesters. The parameter combination of the cleaning device was determined by a mathematical model of materials and airflow. Guo et al. [17] studied the radial distribution rule of the extrudates of the longitudinal axial flow threshing separation device on a combine harvester. In the longitudinal axial flow threshing separation and cleaning test bench developed by themselves, a longitudinal axial flow threshing drum with trapezoid plate teeth and nail teeth were used to conduct rice test studies, and the radial distribution rule of the extrudates of the longitudinal axial flow threshing separation device was analyzed. By comparison, it is concluded that the radial distribution of extrudates is more uniform when the longitudinal axial flow drum adopts nail teeth, which is conducive to cleaning under the premise of the same feeding amount. Chai et al. [18] developed an adaptive guiding bar system to address the uneven transverse distribution of threshed material from the tangential axial flow threshing drum on a cleaning sieve, effectively improving the uneven distribution of discharged material. Yi et al. [19,20] studied the distribution patterns of discharged material from two different threshing separation devices. Fit distribution curves in experimental data revealed that the distribution patterns of discharged material from both devices along the axial direction followed a Peal–Reed model. Fu et al. [21,22] investigated the influence of different experimental factors on the particle size distribution and mass distribution of corn threshing mixtures. Results showed that the mass distribution of corn grains was higher on both sides and lower in the middle in the radial direction, while in the axial direction, it increased first and then decreased. Chen et al. [23] conducted single-factor experiments on the axial and radial distribution changes of a longitudinal axial flow flexible soybean threshing device. The results indicated that the axial distribution of discharged material from the longitudinal axial flow flexible threshing device followed an exponential function, and the radial distribution curve was in the form of polynomials with different coefficients. Qu et al. [24], through experiments on the distribution characteristics of discharged mixtures from corn threshing, concluded that the lower the drum speed, the larger the concave clearance, and the smaller the feeding amount, the lower the mass of grains in the discharged mixture. Zong et al. [25], through experimental research on the distribution characteristics of fully matured rapeseed discharge, concluded that the cumulative separation rate of corn kernels in the front 3/4 section of the drum was above 97.3%, indicating that corn kernel separation was essentially complete, and the drum length could be appropriately shortened. Wang et al. [26], based on probability theory, established a mathematical model for grain separation and obtained a relationship curve between the loss rate of entrained grains, the cumulative separated grain amount, and the unthreshed grain rate after separation for a single axial flow drum. Fu et al. [27] and others, based on a mathematical model of grain separation, used EDEM software to simulate the distribution patterns of a conical rod tooth longitudinal axial flow threshing separation device. They obtained axial and radial distribution curves of post-threshing mixtures along the drum and validated the results through bench tests, which were essentially consistent with the simulation results.

However, existing research has primarily focused on the distribution of threshed mixtures from single longitudinal axis threshing devices, and there is a lack of studies on the distribution of threshed mixtures from double longitudinal axis threshing devices. Threshing and cleaning operations together account for about 17% of the total post-harvest loss, which has a large impact on the quality of the harvest [28]. Therefore, this paper takes the previously developed double longitudinal axis threshing device as the experimental object and conducts single-factor experiments to investigate the distribution of the threshed mixture. Through these experiments, we have obtained the distribution of the threshed

mixture along the axial and radial directions under different experimental factors. Finally, through regression analysis, the distribution curve of the threshed mixture along the roller axis and radial direction was obtained. These research findings serve as valuable references for the design of double longitudinal axis flow cleaning systems.

## 2. Materials and Methods

### *2.1. Structure of the Double Longitudinal Axial Flow Threshing Device*

The double longitudinal axial flow threshing device test bed was independently designed and developed by the team. It is mainly composed of a feeding hopper, top cover, threshing drum, concave screen, material box, frame, and power system, as shown in Figure 1. The feeding hopper, top cover, threshing drum, and concave screen are all symmetrically distributed. To promote the orderly axial movement of crops, there is a deflector plate below the top cover. The threshing drum is connected to the fixed plate above the frame through bolts and bearing seats, and its rotation speed is controlled by a motor. It is equipped with spiral-distributed threshing elements on its surface. Below the threshing drum, there are uniformly arranged material boxes in 27 rows and 13 columns, designed for receiving the grains. Each region has dimensions of 100 mm × 100 mm × 200 mm, as shown in Figure 2.

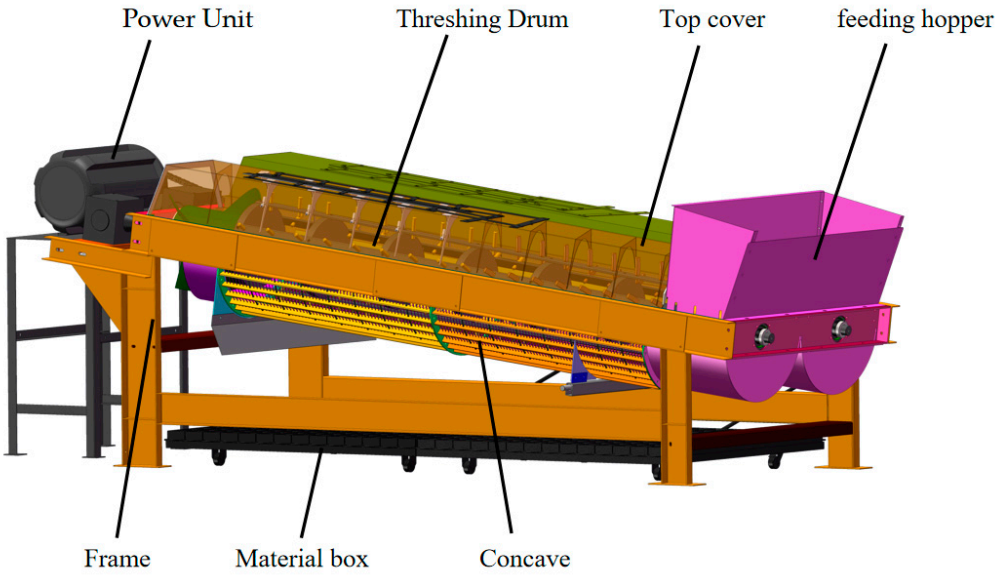
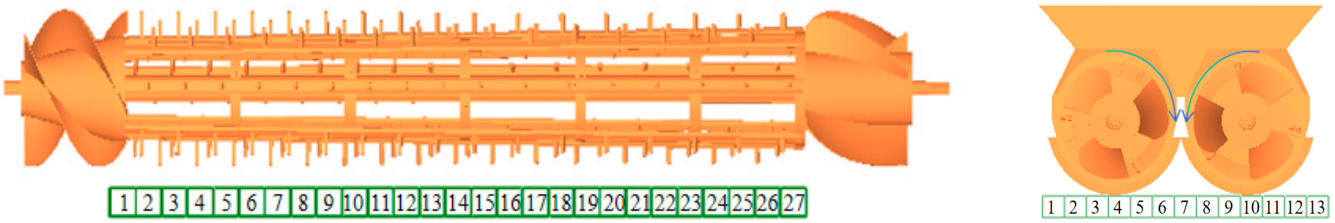



**Figure 1.** Structure diagram of the double longitudinal axial flow threshing device.




(**a**) Axial direction of the drum. (**b**) Radial direction of the drum.

**Figure 2.** Structure diagram of the distribution of the material box along the axial (**a**) and radial (**b**) directions.

The double longitudinal axial flow threshing device adopts the threshing process of radial feeding and axial discharge. During operation, the two threshing drums rotate in opposite directions. Crops are fed into the threshing chamber by a conveying device from the feeding hopper, and, under the forced conveying of the spiral feeding head, they are

continuously and uniformly fed into the compartment formed by the drum, concave, and top cover. As the drum rotates, crops, in close contact with the concave and the curved surface formed by the top cover inside the enclosed cylinder, undergo a spiral motion. Guided by the deflector plate, they move backward along the axis of the drum. Separation is achieved by cyclic impact, squeezing, friction between crops, threshing elements, and the concave. The separated grains fall into the material box through the centrifugal force of the drum, while impurities are discharged from the tail of the drum, thus completing the entire threshing process. The key structural parameters of the double longitudinal axial flow threshing device are shown in Table 1.

**Table 1.** The key structural parameters of the double longitudinal axial flow threshing device.

| Structural Parameter | Value |
|---|---|
| Threshing drum length/mm | 3330 |
| Threshing drum diameter/mm | 550 |
| Concave clearance/mm | 30–70 |
| Concave plate covering corner/(°) | 153 |
| Threshing element | nail tooth |
| Flow guide plate angle/(°) | 30 |

### *2.2. Experimental Material*

The experiment was conducted in Shandong Tiankaizhongrui Machinery Technology Co., Ltd. (Weifang, China). The total mass of preparative corn ears was 5000 kg. The corn cultivar was "Jin wan yu 767", and the average moisture content of corn kernels was 28.7%. The threshed mixture was mainly composed of corn kernels and corn cobs.

### *2.3. Experimental Method*

To obtain the distribution of the threshed mixture in the double longitudinal axial flow threshing device, single-factor experiments were conducted. Based on previous bench tests, the experimental factors chosen for their significant impact on grain threshing were drum speed, threshing clearance, and feed rate, as indicated in Table 2.

**Table 2.** Single-factor experimental scheme design.

| Numbers | Factors | Values | Condition |
|---|---|---|---|
| 1–5 | Drum speed (r/min) | 300, 350, 400, 450, 500 | Concave clearance = 50 mm<br>Feed rate = 16 kg/s |
| 6–10 | Concave clearance (mm) | 40, 45, 50, 55, 60 | Drum speed = 400 r/min<br>Feed rate = 16 kg/s |
| 11–15 | Feed rate (kg/s) | 14, 15, 16, 17, 18 | Drum speed = 400 r/min<br>Concave clearance = 50 mm |

Before the experiment, the corn of the required mass for a single trial was weighed using an electronic scale and evenly spread on the conveyor, leaving a sufficient acceleration zone. The drum speed was adjusted to the desired level using a frequency converter, and after stabilizing, the conveyor was started. Following each trial, the discharged material was sequentially collected from the material box. It was then weighed and recorded using an electronic scale with a precision of 0.1 g. Each experiment was conducted three times, and the average was taken. The physical setup of the experimental platform for the double longitudinal axial flow threshing device is illustrated in Figure 3.



**Figure 3.** Experimental platform for the double longitudinal axial flow threshing device.

## 3. Results and Discussion

The distribution of the threshed mixture in the material box is shown in Figure 4.

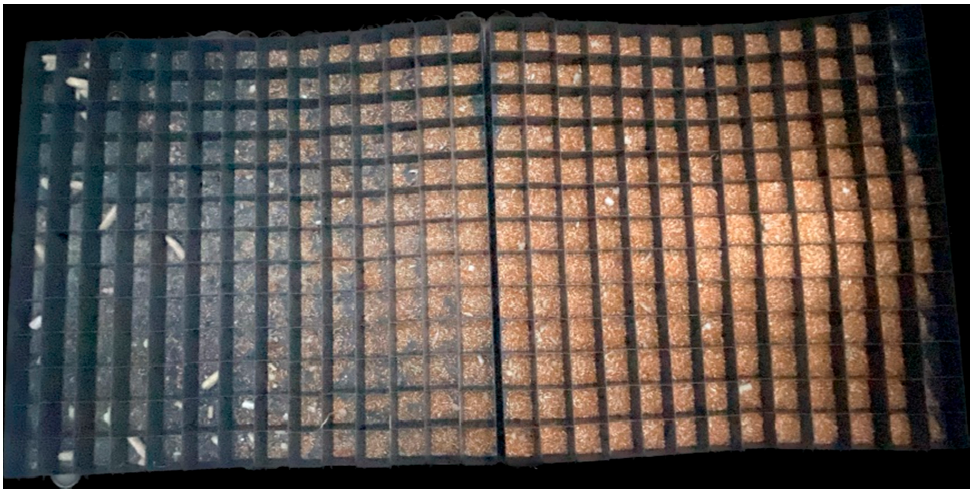
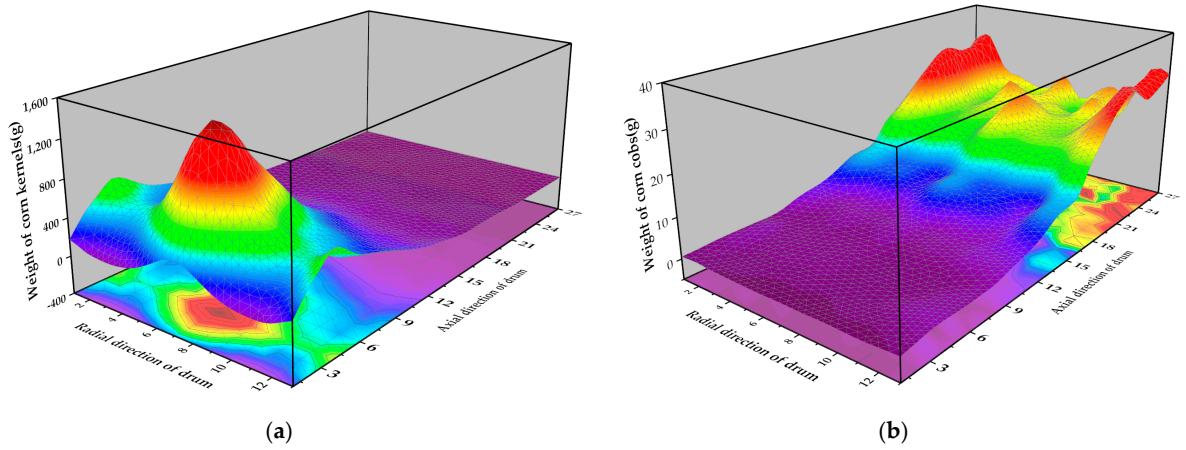


**Figure 4.** Pattern of the mass of the mixture.

In order to observe the axial and radial variation trend of the expelled mixture along the drum more comprehensively, Origin software was used to draw a three-dimensional mass distribution diagram of the expelled mixture, as shown in Figure 5.

Due to the complexity of the threshing process, the distribution of the mixture along the drum in the axial and radial directions is not completely symmetrical. It can be seen in Figure 5a that the mass of corn grains increases first and then decreases along the axis of the drum. In the radial direction, corn grains are approximately distributed in the shape of a "W" at the front 3/1 of the drum, with obvious accumulation in the middle and both sides, among which the middle mass is the largest. As can be seen in Figure 5b, the mass of the corn cob axis is increasing along the axial direction, and the distribution in the radial direction is very uneven, and the maximum mass is on both sides.

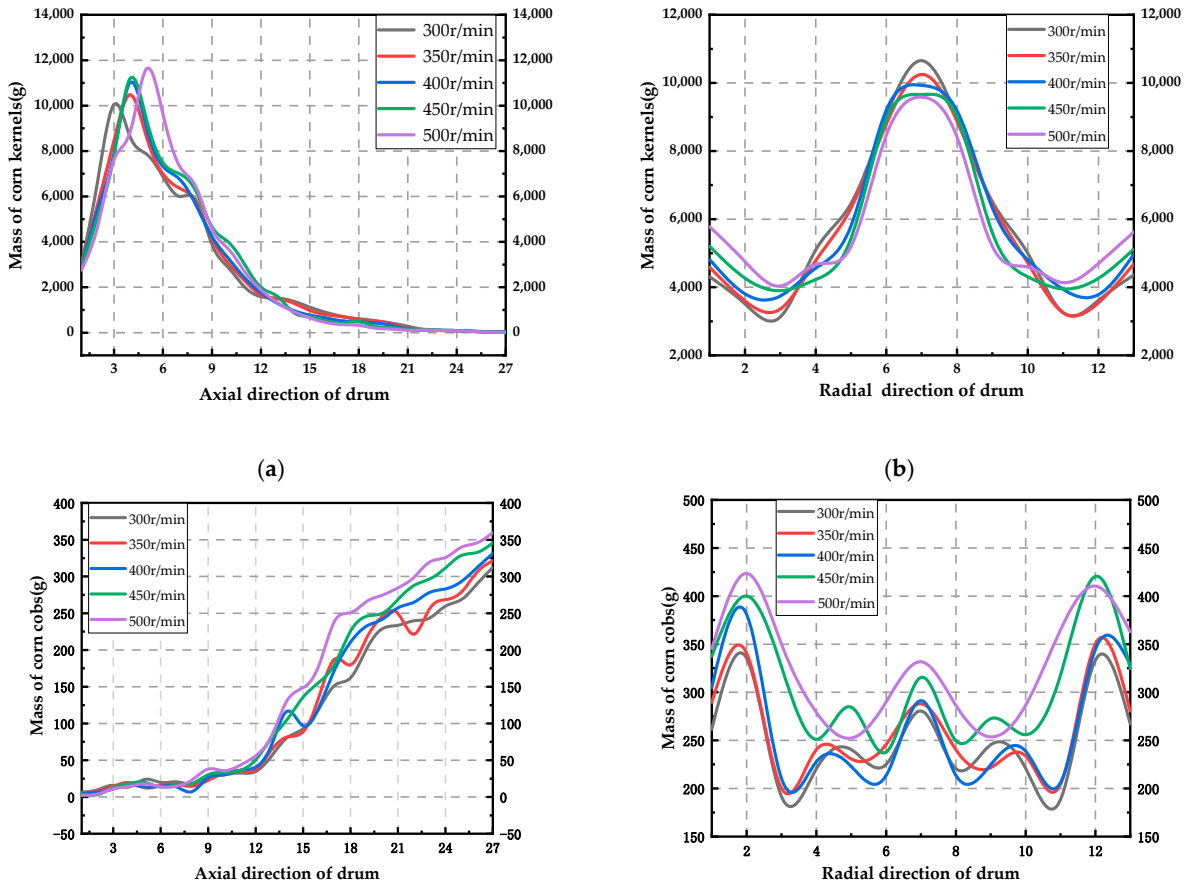



(**a**) (**b**)

**Figure 5.** Three-dimensional distribution of the weight. (**a**) Mass distribution pattern of the corn kernels. (**b**) Mass distribution pattern of the corn cobs.

### *3.1. Effect of Drum Speed on the Mass Distribution of the Threshed Mixture*

Under the conditions of a threshing gap of 50 mm and a feed rate of 16 kg/s, experiments were conducted at drum speeds of 300, 350, 400, 450, and 500 r/min, respectively. The mass distribution of the extracted material along the axial and radial directions at different drum speeds was obtained, as shown in Figure 6.




(**a**) (**b**)

(**c**) (**d**)

**Figure 6.** Mass distribution of the threshed mixture for different drum speeds. Mass distribution curves in the axial and radial directions of (**a**,**b**) corn kernels; (**c**,**d**) corn cobs.

#### 3.1.1. Effect of Drum Speed on the Kernel Mass Distribution of Maize

The distribution of corn grain mass along the axis was similar under different drum speeds, and the overall trend was rapidly increasing and then decreasing. As the drum speed increased, the peak value of corn grain mass moved backward, and the overall quality continued to rise (Figure 6a). The increase in drum rotation speed leads to an amplified impact force of the threshing element on the ear, thereby accelerating grain movement and resulting in an increased mass. Consequently, the peak value continuously shifts backward along the axial direction of the drum. In the radial direction, corn grain mass presents a "w" distribution, with obvious accumulation on both sides and in the middle, and the middle mass is the highest. With an increase in the rotating speed of the drum, the peak value of corn grain mass decreases, and the corn grain falling on both sides of the drum keeps rising (Figure 6b). This is because during the threshing process, the grains become loose in the upper half of the drum, which is the primary process of grain separation [29,30]. According to the rotation direction of the double longitudinal axial flow threshing drum, the highest quality grains are located in the middle. Additionally, under the influence of centrifugal force, the maize grains falling on both sides of the drum have slightly lower quality. As the speed of the drum increases, the centrifugal force acting on the grains intensifies, making the separated grains more conducive to separating toward both sides.

#### 3.1.2. Effect of Drum Speed on the Cob Mass Distribution of Maize

In the axial direction, the mass of corn cob axes steadily increases, especially beyond the 12th row, showing a rapid growth trend in mass. Simultaneously, with an increase in drum speed, the total mass of corn cob axes continues to rise (Figure 6c). This was initially due to the corn ears being intact and the grains having not yet detached from the ears. The cob axes are enveloped within the grains, reducing the probability of contact with the threshing elements. As threshing progresses, a significant number of grains dislodge from the cob axes, exposing them to the threshing drum. This increased exposure enhances the probability of contact with the threshing elements, leading to the fracture and detachment of the cob axes. Additionally, as the drum speed increases, the rapid removal of corn grains further intensifies the impact force exerted by the threshing elements on the ears. This results in the separation of more broken cob axes. In the radial direction, the mass of the cob axes exhibits a wavelike distribution, with a generally consistent trend under different speeds. The mass is the highest on both sides, and as the drum speed increases, the peak mass of the cob axes continues to rise. This results in a decrease in radial distribution uniformity, increasing the load on the cleaning system (Figure 6d). This was due to the corn cob axes having a relatively light mass, and the inertial force generated after colliding with the threshing components is small. Most of them will fall freely, leading to poor radial distribution. As the drum speed increases, the centrifugal force comes into play, causing more corn cob axes to be ejected toward the outer side of the drum, resulting in an increase in mass on both sides.

### *3.2. Effect of Concave Clearance on the Mass Distribution of the Threshed Mixture*

Under the conditions of a drum speed of 400 revolutions per minute (r/min) and a feed rate of 16 kg/s, experiments were conducted with concave clearance set at 40, 45, 50, 55, and 60 mm. The results illustrate the axial and radial mass distribution of the discharged material at different concave clearances, as shown in Figure 7.

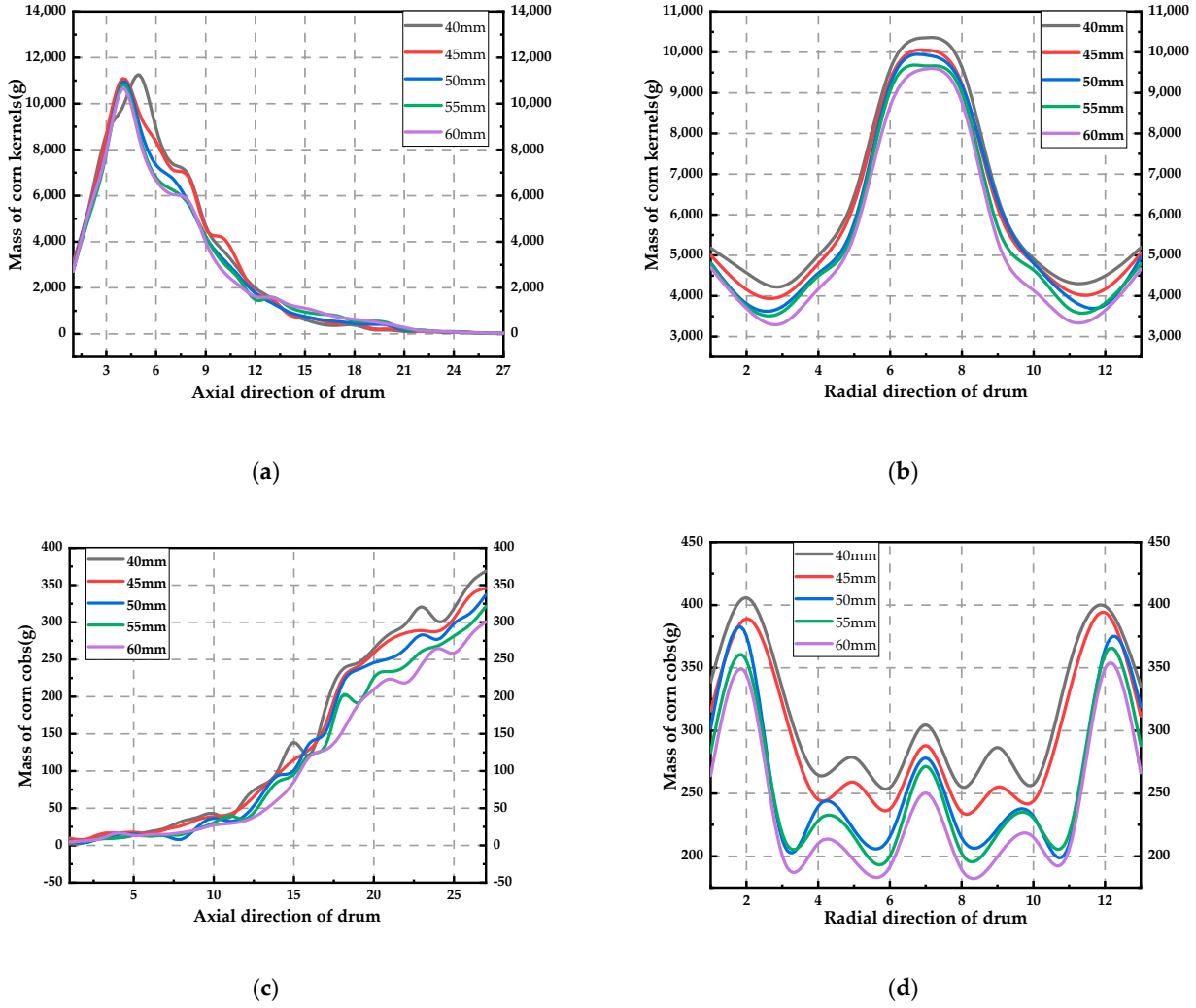



**Figure 7.** Mass distribution of the threshed mixture for different concave clearances. Mass distribution curves in the axial and radial direction of (**a**,**b**) corn kernels; (**c**,**d**) corn cobs.

#### 3.2.1. Effect of Concave Clearance on the Kernel Mass Distribution of Maize

The distribution of corn kernel mass along the drum axial direction is similar under different concave plate clearances. Overall, it exhibits a trend of initially increasing and then decreasing. As the concave clearance increases, the total mass of the kernels continuously decreases, and the peak mass shifts to the left along the axial direction of the drum (Figure 7a). This was due to an increase in the gap between the concave plates, and the threshing element and the ear cannot fully contact, so the unthreshed corn grains are discharged along the corn cob axis, resulting in corn kernel loss. In addition, too small of a threshing space will make a large amount of the mixture mix together, and the corn kernels cannot be discharged in time, resulting in the mass peak moving backward. Similarly, in the radial direction, as the concave clearance increases, the overall mass of kernels decreases continuously. A larger concave clearance results in a more uniform distribution of kernels (Figure 7b). This was due to the increase in concave clearance that leads to a loosening of the material layer in the threshing space, making maize kernels more prone to falling through the concave under the action of centrifugal force.

#### 3.2.2. Effect of Concave Clearance on the Cob Mass Distribution of Maize

In the axial direction, the mass of the maize cob axis continuously increases and has a noticeable increase beyond the 12th row (Figure 7c). As mentioned earlier, after the kernels are threshed, the probability of contact between the maize cob axis and the threshing

element increases, leading to a rapid increase in its mass. However, with an increase in concave clearance, the overall mass of the maize cob axis decreases. This is because the threshing space is too large, and the threshing element cannot fully contact the corn cob shaft. In the radial direction, with an increase in concave clearance, the total mass of the corn cob axis continues to decrease, and the distribution becomes more uniform (Figure 7d).

### *3.3. Effect of the Feed Rate on the Mass Distribution of the Threshed Mixture*

Under the conditions of a drum speed of 400 revolutions per minute and a threshing clearance of 50 mm, experiments were conducted using feed rates of 14, 15, 16, 17, and 18 kg per second. The resulting mass distribution of the discharged material along both the axial and radial directions at different feed rates is illustrated in Figure 8.

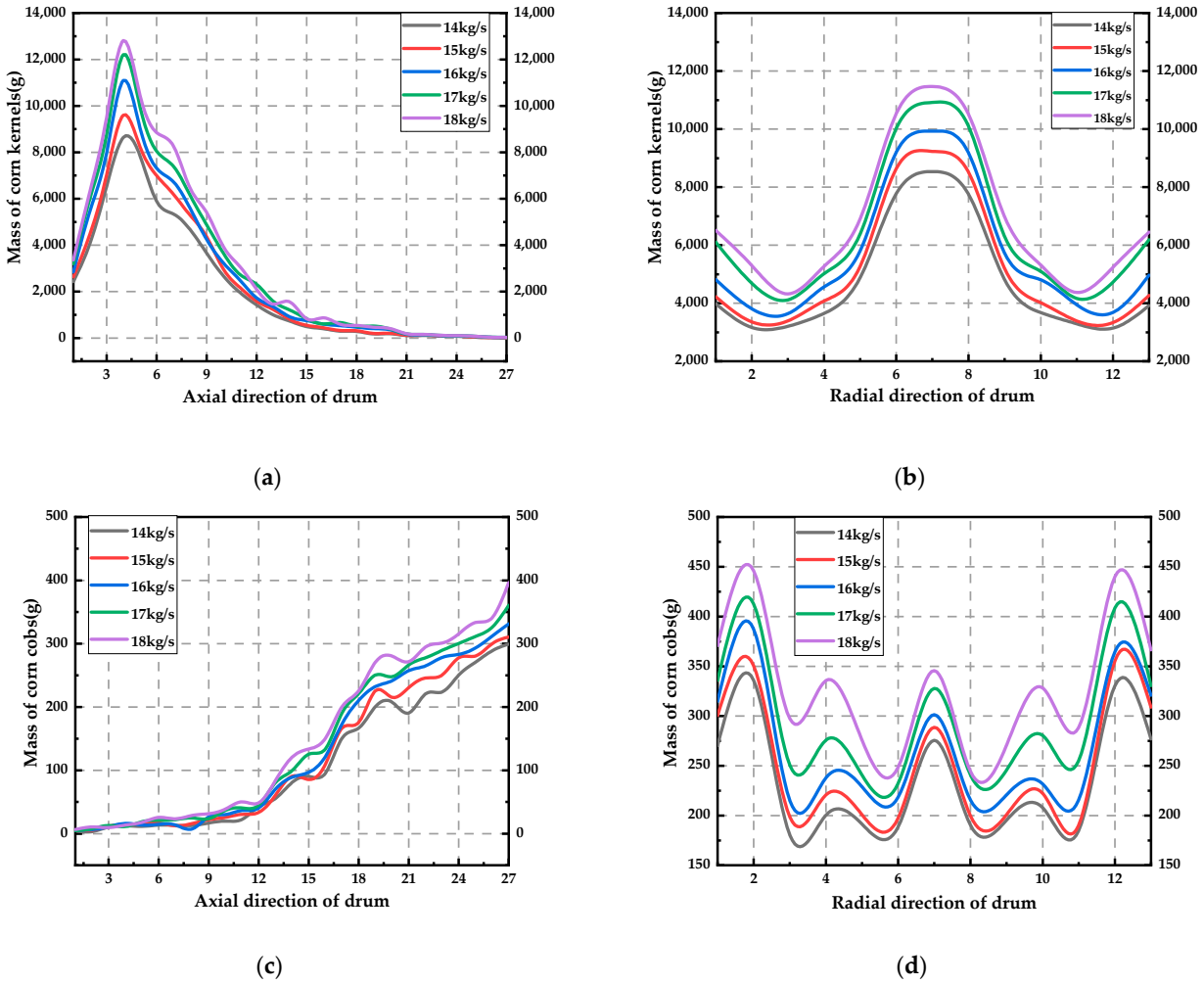



**Figure 8.** Mass distribution of the threshed mixture for different feed rates. Mass distribution curves in the axial and radial direction of (**a**,**b**) corn kernels; (**c**,**d**) corn cobs.

#### 3.3.1. Effect of the Feed Rate on the Kernel Mass Distribution of Maize

The distribution pattern of corn grain mass along the axial direction remains similar at different feed rates, showing an overall trend of initially increasing and then decreasing (Figure 8a). With an increase in the feed rate, both the peak and overall mass of corn grain continuously rise. However, the proportion of separated corn grain mass to the total grain mass decreases. This is because an excessive feed rate results in too thick of a layer of material inside the threshing chamber. As a consequence, the separated corn grains cannot pass through the concaves effectively, leading to higher grain losses. In the radial direction, the distribution of corn grain mass is uneven, presenting an overall "W"-shaped pattern

(Figure 8b). With an increase in the feed rate, the accumulation of grains along the middle and sides of the drum becomes more pronounced, which is detrimental to the subsequent cleaning process.

#### 3.3.2. Effect of the Feed Rate on the Cob Mass Distribution of Maize

In the axial direction, the mass of the corn cob axis exhibits a trend of slow initial growth followed by rapid increase. With an increase in the feed rate, both the peak and overall mass of the corn cob axis continuously rise (Figure 8c), concurrently increasing its proportion in the discharged mixture. In the radial direction, the trend in the mass variation of the corn cob axis is generally consistent. As the feed rate increases, the overall mass of the corn cob axis increases, and there is a more pronounced accumulation on both sides (Figure 8d).

### *3.4. Discussion*

The experimental study on the distribution pattern of corn discharge in the double longitudinal axial flow threshing device reveals the following findings. The total mass of corn kernels in the experiment continues to increase. Among them, the corn kernels along the axial front 2/3 section of the threshing drum account for 88% to 94% of the total kernel mass. This indicates that corn kernels undergo significant separation in the first two-thirds of the threshing drum, aligning with the distribution pattern observed in a single longitudinal axial flow corn threshing device [21,24].

The impact of drum speed on the distribution pattern of ejected material is particularly significant. As the drum speed increases, the fluctuation in the curve depicting the variation in ejected material mass becomes more pronounced. In comparison, the effects of the concave clearance and feed rate on the distribution of ejected material mass are relatively minor. Enlarging the concave clearance and reducing the feed rate result in a more uniform radial distribution of the ejected material, reducing core axis mass and mitigating the accumulation of the ejected material to some extent. However, during the experimental process, it was observed that too low of a drum speed, an insufficient feed rate, or excessive concave clearance could lead to the incomplete detachment of grain spikes, thereby diminishing the quality of harvested corn kernels [31]. Considering the grain breakage rate and unthreshed rate, the optimal operational parameter combination was determined as follows: a drum speed of 400 r/min, a feed rate of 16 kg/s, and a concave clearance of 50mm. Under this optimized condition, repeated experiments were carried out three times, experimental data were collected, and the regression fitting curves of the axial and radial distribution of the mixture along the drum after threshing were obtained using Origin software (Figure 9). Meanwhile, analysis of variance was performed (Table 3).

**Table 3.** Regression equation of the axial distribution of the threshed mixture along the drum.

| Drum Direction | Name | Regression Equation | $R^2$ | $p$ |
|---|---|---|---|---|
| axial | corn kernels | $y_1 = \frac{2360.015+209.089x}{1-0.322x+0.38x^2}$ | 0.97 | <0.001 |
| radial | corn kernels | $y_2 = 4871.563 - 5766.879x_1 + 4480.413x_2 - 1810.679x_3 + 358.640x_4 - 22.760x_5 - 2.856x_6 + 0.569x_7 - 0.034x_8$ | 0.99 | <0.05 |
| axial | corn cobs | $y_3 = 340.967 - \frac{330.146}{1+\left(\frac{x}{17.285}\right)^{5.632}}$ | 0.99 | <0.001 |
| radial | corn cobs | $y_4 = -320.402 + 1166.137x_1 - 711.969x_2 + 218.923x_3 - 42.860x_4 + 6.162x_5 - 0.660x_6 + 0.047x_7 - 0.001x_8$ | 0.94 | <0.05 |

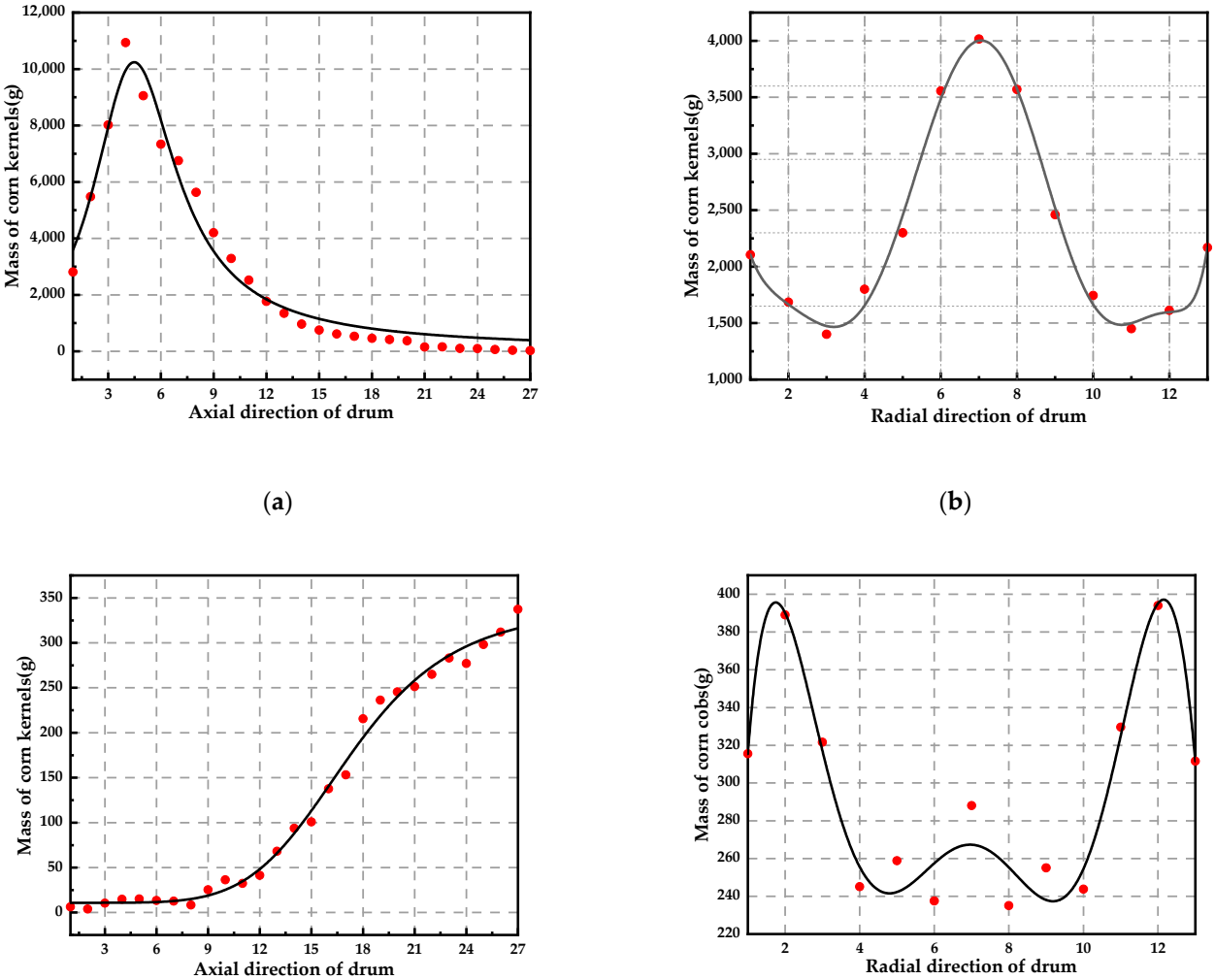



**Figure 9.** The fitting curves of the axial distribution of the threshed mixture along the drum. (**a**) Regression equation of the axial distribution of corn kernels along the drum. (**b**) Regression equation of the radial distribution of corn kernels along the drum. (**c**) Regression equation of the axial distribution of corn cobs along the drum. (**d**) Regression equation of the radial distribution of corn cobs along the drum.

$R^2$ refers to the correlation coefficient of the regression equation. $p < 0.05$ means significant, and $p < 0.001$ means extremely significant.

The axial distribution of corn kernels in the double longitudinal axial flow corn threshing device is consistent with $y = \frac{a+bx}{1-cx+dx^2}$, and the axial distribution of corn cobs axis is consistent with $y = a + \frac{a-b}{1+\left(\frac{x}{x_0}\right)^p}$; the radial distribution pattern of the threshed mixture adheres to the equation $y = a_0 + a_1x^1 + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 + a_7x^7 + a_8x^8 + a_9x^9$. In conclusion, this paper obtained the regularities of distribution of the threshed mixture of the double longitudinal axial flow corn threshing device by a single-factor experiment, which provides a design basis for the structural improvement of the double longitudinal axial flow corn threshing device and the distribution of the fan air volume in the cleaning system so as to reduce the impurity rate and loss rate of the threshers.

## 4. Conclusions

This study systematically investigated the effects of the drum speed, threshing clearance, and feed rate on the distribution of the threshed mixture in both the axial and radial directions of a double longitudinal axial flow threshing device by single-factor experiments. The findings are summarized as follows:

(1) The mass distribution of mixed maize discharge exhibits non-uniform patterns along both the axial and radial directions of the drum. In the axial direction, the mass of maize grains initially increases and then decreases, concentrating primarily in the front 1/3 of the drum, while the mass of maize cob axis continues to increase, particularly after the 1/3 point of the drum, showing a trend that is consistent with the discharge pattern of a single longitudinal axial flow corn threshing device along the axial direction. In the radial direction, maize grains exhibit a "W"-shaped distribution with accumulation in the middle and on both sides, where the middle has the highest mass. Meanwhile, the maize cob axis shows a wave-like distribution, with the highest mass on both sides.

(2) The degree of influence of each experimental factor on the distribution of the discharge mixture along the axial and radial directions varies, with the drum speed having the most significant impact. The experiments indicate that a slower drum speed, a larger threshing clearance, and a smaller feed rate result in a more uniform distribution of the discharged mixture. Combining the grain breakage rate and unthreshed rate, the optimal operational parameter combination for the double longitudinal axial flow threshing device is determined to be a drum speed of 400 r/min, a feed rate of 16 kg/s, and a concave clearance of 50 mm. These findings provide a valuable reference for the structural design optimization of the double longitudinal axial flow threshing device, as well as the cleaning system.

**Author Contributions:** Conceptualization, D.Y. and D.G.; methodology, D.Y. and M.L.; software, D.Y.; validation, D.Y., D.G. and D.L.; formal analysis, D.Y.; investigation, D.Y.; resources, Q.W.; data curation, D.Y.; writing—original draft preparation, D.Y.; writing—review and editing, D.G.; visualization, Q.H., D.L. and Q.Y.; supervision, D.G.; project administration, D.G.; funding acquisition, D.G. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

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