In-field harvest loss of mechanically-harvested maize grain and affecting factors in China

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Abstract: Field harvest loss is a common problem of maize grain mechanical harvesting in China and abroad. From 2012 to 2019, 2987 groups of samples for the quality of mechanical grain harvesting in field were obtained in 21 major maize-producing provinces, cities, and regions of China. The analysis performed in this study showed that the average harvest loss of fallen ears was equivalent to 76.5% of the total harvest loss, indicating that the harvest loss in the mechanical harvesting of maize grain mainly came from the loss of fallen ears. Meanwhile, statistical analysis of the harvest loss in different ranges of grain moisture contents showed that, when the grain moisture content fell below 20%, the harvest loss rate of fallen ears and the total harvest loss rate both increased sharply, and the harvest loss of fallen ears increased faster than the harvest loss of fallen grain with a decreasing grain moisture content. Moreover, the results of multi-point experiments and harvest experiments in different periods showed that, during harvesting time, the harvest loss of fallen ears caused by lodging was the main reason for in-field harvest losses in the mechanical harvesting of maize grain. Apart from the above mentioned, the test results of 35 groups of harvesters for the in-field mechanical harvesting of maize grain showed that the harvester types and their operating parameters were important factors affecting the harvest loss in the mechanical harvesting of maize grain. Therefore, the principal paths to reduce harvest loss in the mechanical harvesting of maize grain are to breed lodging-resistant maize varieties, adopt reasonable planting densities, cultivate healthy plants, develop harvesters with low harvesting loss, intensify the training of operators, and harvest at an appropriate time.

Keywords: maize grain, mechanical harvest, harvest losses, affecting factors, fallen ears, fallen grain

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1 Introduction

Maize harvest loss, which includes ear loss and grain loss, is a common problem of mechanical harvesting of maize grain in many countries[1-3]. Sumner et al[3] reported that the harvest loss rate in the mechanical harvesting of maize grain is generally between 2% and 4% of the yield. According to research from Ohio State University[4], under normal harvest conditions, the harvest loss from fallen ears should not exceed 1% of the yield, the threshing loss should not exceed 0.3%, and the loss from fallen grain due to other causes should not exceed 0.5%, that is, the total harvest loss should not exceed 1.8% of the yield. Additionally, Paulsen[5] found that, in Brazil, the total harvest loss in the mechanical harvesting of maize were 36.2-320.6 kg/hm^2, which was equivalent to 0.3%-3.6% of the yield. In 2017, the research team of this study (the innovation team of crop cultivation and physiology of CAAS, China) analyzed 1698 groups of samples for harvest quality, which were obtained from mechanical harvesting tests of maize grain conducted in 168 sites in 15 provinces, cities, and regions of China from 2011 to 2015. It was found that, in the mechanical harvesting of maize grain, the average harvest loss from fallen ears and fallen grain was 24.71 g/m^2, equivalent to 247.5 kg/hm^2, or 4.12% of the yield. There was a large difference among the fields, with the minimum loss being 0.10 g/m^2 (1.01 kg/hm^2), the highest loss being 419.88 g/m^2 (4198.5 kg/hm^2), as well as a coefficient of variation of 164.51%. Harvest loss is an important factor restricting the popularization for the mechanical harvesting of maize grain[6] and the harvest loss rate is also an important index not only to evaluate the quality of maize grain harvesting but even to determine the yield. According to the Chinese national standard of "Technical Conditions for Maize Harvesting Machinery"[7], the harvest loss rate should be less than or equal to 5% of the yield. In the 1970s, technology for the mechanical harvesting of maize grain began to be widely applied in Europe and North America[8], and a large amount of research was carried out on the form of harvest loss[9,10], the causes of harvest loss[11-19], and measures to reduce this loss[20-29], which has provided technical support for the breeding progress of maize varieties and the

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improvement of mechanical grain harvesting technology. Previous research has shown that the in-field harvest loss mainly came from the loss of ear-falling before harvest—which can be caused by intrinsic properties of maize varieties, damage from maize borer, stalk lodging during harvesting, as well as the loss from fallen ears and fallen grain during mechanical harvesting[30,31]. Different types of harvesters and different harvesters of the same type both can be associated with harvest losses in field[32] since such losses are related to the type of mechanical harvesting device, the working principle, the header speed, the rotation speed of the threshing cylinder, the screen clearance, the fan speed, etc[10,11,14,15,17,19,21]. In China, mechanical harvesting of maize grain was introduced relatively later and is currently applied in less than 10% of the total planting area of maize, and there are great differences in ecological types, planting modes, maize varieties, harvesting machinery, and other conditions in areas where mechanical harvesting of maize grain is applied. The lack of research on the harvest loss from the mechanical harvesting of maize grain has seriously restricted the application and promotion of this technology. In this study, based on an extensive investigation of the quality of mechanical grain harvesting in various maize-producing areas in China, combined with the results of multi-point experiments on the relationship between maize lodging and harvest loss, as well as comparative tests of different harvesters, the current situation of harvest loss from mechanical harvesting of maize grain in China was studied and its relevant causes were analyzed. Hereby, countermeasures to reduce the harvest loss were proposed, thus providing support for the progress of the mechanical harvesting of maize grain in China.

2 Materials and methods

2.1 Harvest loss test of mechanical harvesting of maize grain in fields

From 2012 to 2019, during the harvesting season, mechanical grain harvest experiments and field harvest quality surveys were carried out at 155 sites distributed in 21 major maize-producing provinces, cities, and regions in China, including Northwestern China irrigated maize region (NW, including Xinjiang, Gansu, Ningxia, northern Shaanxi, and central and western Inner Mongolia), the Northeastern China spring maize region (NE, including Liaoning, Jilin, Heilongjiang, and four leagues in eastern Inner Mongolia), the Huang-Huai-Hai summer sowing maize area (HH, including Henan, Hebei, Shandong, Jiangsu, Anhui, and the Guanzhong Plain of Shaanxi), the Northern China spring maize area (NC, including Beijing, Tianjin, and Shanxi), and the Southwestern China maize region (SW, including Sichuan Province, Yunnan Province, Hunan Province, Hubei Province, Tibet Region). 2987 groups of survey data were acquired, comprising 8961 samples of in-field mechanical grain harvesting.

2.2 Multiple experiments on the relationship between harvest loss and maize lodging in field

In 2018-2019, multiple experiments consisting of 14 tests of harvest quality were carried out at 11 experimental sites, namely, Keshan County, Jiamusi City, Chifeng City, and Tieling City in Northeastern China spring maize area, Hengshui City, Laizhou County, Luoyang City, Yanjin County, Dezhou City, and Liaocheng City in the Huang-Huai-Hai summer sowing maize area, and Yongning County in Northwestern China irrigated spring maize area. Maize was planted under the local production and field management mode in each site, respectively. Harvest loss was evaluated infield during mechanical grain harvesting and the lodging rate of maize plants was measured simultaneously. Thereby, a total of 163 groups of sample data were obtained (Table 1).

Table 1 Results of multiple experiments on the relationship between maize harvest loss and lodging in field

Year	Site	Number of cultivars	Harvest date (m-d)	Remarks
2018	Dezhou, Shandong	10	09-29	
	Liaocheng, Shandong	14	09-30	
	Yanjin, Henan	7	10-03	
	Jiamusi, Heilongjiang	13	10-06	
	Hengshui, Hebei	8	10-06	
	Luoyang, Henan	10	10-07	
	Keshan, Heilongjiang	14	10-14	
2019	Laizhou, Shandong	8	09-19	
	Yanjing, Henan	7	09-24	
	Liaocheng, Shandong	13	10-11	
	Chifeng, Inner Mongolia	13	10-17	
	Keshan, Heilongjiang	13	10-18	
	Yongning, Ningxia	6	10-21	
	Tieling, Liaoning	3	10-10 10-25 11-05	The 3 cultivars were planted at 3 different planting densities and harvested respectively

2.3 Comparative experiments of the influence of harvester type and its operation parameters on harvest loss

From 2012-2019, 35 groups of comparative tests for the mechanical harvesting of maize grain were conducted, respectively, in Xinjiang Region, Gansu Province, Ningxia Province, Jilin Province, Liaoning Province, Henan Province, Anhui Province, Hebei Province, and other provinces and cities of China. These tests involved different harvester types, harvester running speeds, cylinder rotation speeds, row spacing and height of maize headers, feeding amounts, tail screen angles, and other parameters. The harvest loss in field was measured and the influence of harvester type and its operation parameters on harvest loss were analyzed.

2.4 In-field Investigation of lodging rate and harvest loss rate

Before the mechanical harvesting of maize grain, an area with a length of 10 m and a cutting width of 4-6 rows of maize plants was randomly picked out as the sample area for lodging investigation. In the area, the total number of plants, the stalk breakage rate, and the root lodging rate was recorded and the total lodging rate (%), was calculated three times as follows: total lodging rate=(stem breakage and root lodging)/total number of plants×100%. Stalk breakage was defined as breakage in the internodes under the maize ear; meanwhile, if the internodes under the ear were not broken and the plant deviated by more than 45° from the vertical, root lodging was diagnosed.

The sample points for the investigation of harvest loss were randomly selected in the harvested maize fields. Each sample point covered an area with a length of 2 m and a cutting width of 4-6 rows of maize plants. All the fallen ears and fallen grain in the sample area were collected, the number of ears was recorded, the fallen ears were threshed manually, and the grain weights of fallen ears and fallen grain were calculated, respectively. Then, in conformity with a grain moisture content of 14% during harvesting, the weight per unit area of fallen ears and fallen grain was measured according to the area of the sample points. The test was also repeated three times. Hence, the harvest loss rate was estimated based on the yield data of the harvested field.

3 Results and analysis

3.1 Harvest loss from the mechanical harvesting of maize grain

The in-field harvest loss includes two aspects: grain loss and ear loss. According to the statistics of the 2987 samples of harvest quality for the mechanical harvesting of maize grain obtained from 2012 to 2019, the average fallen grain loss, average fallen ear loss, and average total loss were 0.114 t/hm^2, 0.351 t/hm^2, and 0.345 t/hm^2, representing 1.33%, 3.25%, and 3.54% of the yield, respectively. The average fallen grain loss and the average fallen ear loss accounted for 23.5% and 76.5% of the total harvest loss, respectively, indicating that the harvest loss mainly came from the loss from fallen ears (Figure 1). Additionally, as it was revealed by a frequency analysis of the harvest loss: 87.7% of the samples had a fallen grain loss of less than 0.2 t/hm^2 and 96.3% of the samples had a fallen grain loss of less than 0.4 t/hm^2; 80.0% of the samples had fallen ear losses less than 0.5 t/hm^2, 90.5% of the samples had a fallen ear loss less than 1.0 t/hm^2; 92.2% of the samples had total harvest losses less than 1.0 t/hm^2. Moreover, 89.4% of the samples had a fallen grain loss of less than 2.5% and 96.4% of the samples had a fallen grain loss of less than 5%; 81.4% of the samples had a fallen ear loss less than 5% and 90.5% of the samples had a fallen ear loss less than 10%; 82.6% of the samples had a harvest loss less than 5%, that is, 18.4% of the sample fields in this study had a total harvest loss of more than 5%.

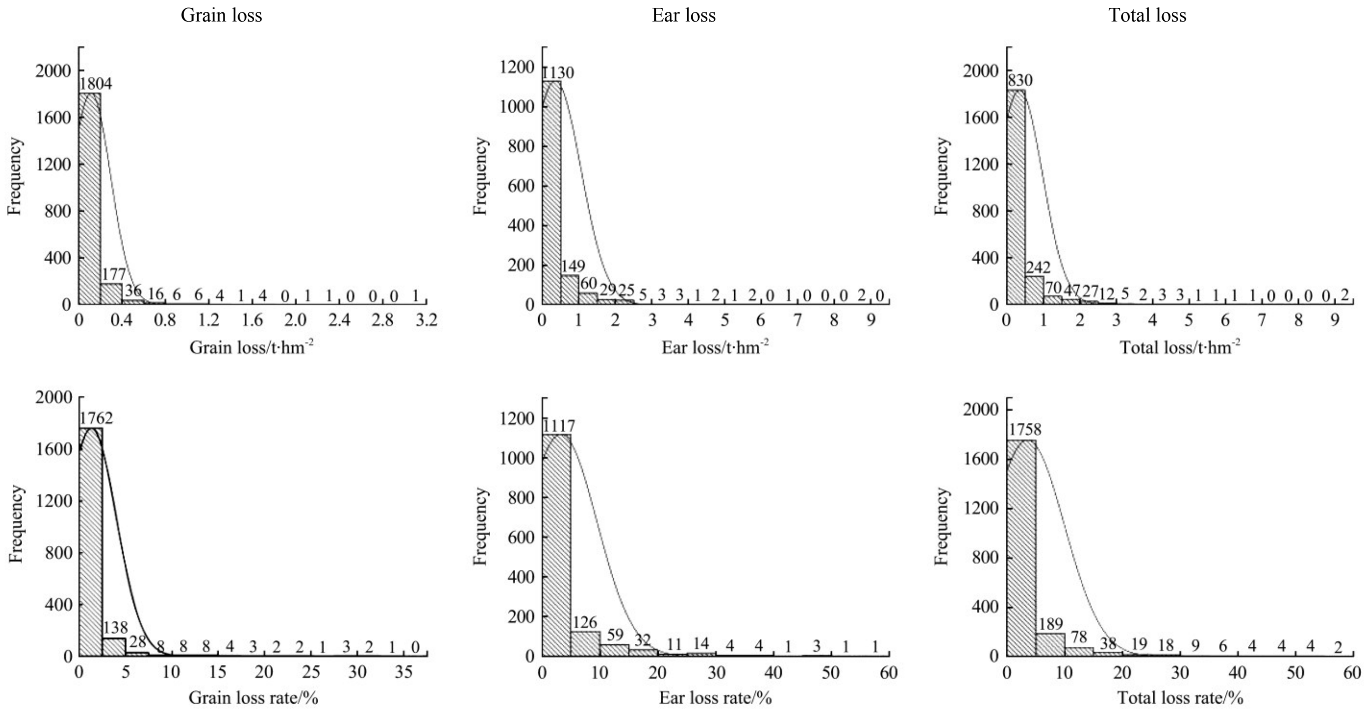


Figure 1 Frequency distribution of harvest loss in maize fields

3.2 Harvest loss under various grain moisture contents during different harvest periods

The grain samples harvested during different periods were divided into different groups based on their moisture content at harvest, namely the ranges of 10%-15%, 15%-20%, 20%-25%, 25%-30%, 30%-35%, and 35%-40%; the effective sample sizes for each of these moisture content ranges were 290, 258, 635, 763, 370, and 66, respectively. The harvest losses of maize for these different moisture content ranges are shown in Figures 2-4. As it is shown in Figure 2, the harvest loss rate of fallen grain is varied parabolically with increasing grain moisture content, fitted by Equation (1):

$$y=0.020x^2+2.974,\ R^2=0.753^{**} \tag{1}$$

where, y is the loss rate from fallen grain, %; x is the grain moisture content, %.

The lowest harvest loss rate of fallen grain was obtained at a moisture content range of 25%-30%, and the harvest loss rate of fallen grain obviously rose when the moisture content fell below 20%. Meanwhile, when the grain moisture content was in the range of 20%-40%, the harvest loss from fallen ears became relatively lower; however, when the grain moisture content was less than 20%, the harvest loss rate from fallen ears obviously rose. As it is shown in Figure 3, the fitted relationship between the grain moisture content and the harvest loss from fallen ears is exponential, namely: $y=7.183e^{-0.03x}$, $R^2=0.718^{**}$, where y is the harvest loss rate of fallen ears and x is the grain moisture content. In the same way, as it is shown in Figure4, the total harvest loss rate increased exponentially with a decreasing grain moisture content (which occurs with the delay of harvesting time), which was similar to the trend observed for the harvest loss from fallen ears. When the grain moisture content was lower than 20%, the total harvest loss rate increased sharply, and the fitting equation between the two parameters is: $y=9.513e^{-0.03x}$, $R^2=0.831^{**}$, where y is the total harvest loss rate and x is the grain moisture content.

Based on the above results, it could be found that, with a decreasing grain moisture content (i.e., with the delay of harvesting time), the loss from fallen ears increased faster than the loss from fallen grains. Specifically, at grain moisture contents of 30%-40%, the harvest loss from fallen ears accounted for 63.0%-64.5% of the total harvest loss, and at grain moisture contents of 20%-30%, the harvest loss from fallen ears accounted for 67.1%-73.6% of the total harvest loss; while at grain moisture contents of 10%-20%, the loss from fallen ears accounted for 74.6%-75.7% of the total harvest loss.

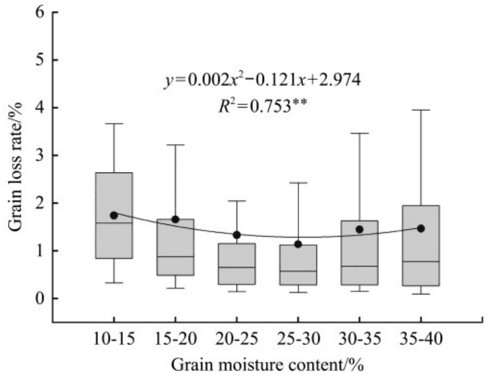


Figure 2 Harvest loss rate of fallen grain in the mechanical harvesting of maize grain under different grain moisture contents

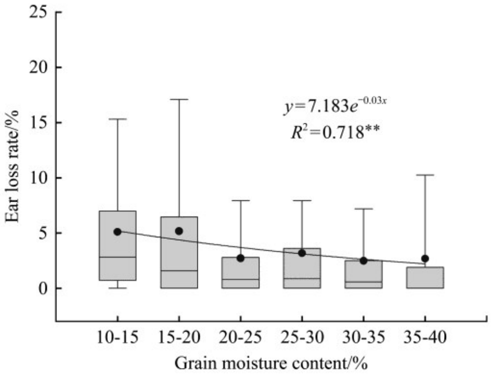


Figure 3 Harvest loss rate of fallen ears in the mechanical harvesting of maize grain under different moisture contents

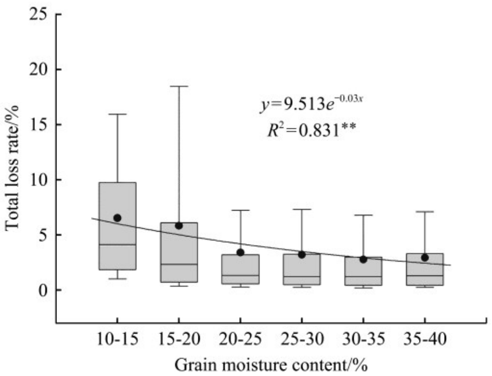


Figure 4 Total harvest loss rate in the mechanical harvesting of maize grain under different moisture contents

3.3 Relationship between harvest loss rate and lodging rate in the mechanical harvesting of maize grain

From 2018-2019, in order to estimate the maize lodging rate in field and the maize harvest loss, 163 groups of sample data were obtained from 14 demonstration fields distributed in 11 experimental sites in China. The results (Table 2) showed that the lodging rate (root lodging and stem breakage) was significantly positively correlated with the loss rate of fallen ears and the total loss rate, but was insignificantly correlated with the loss rate of fallen grain. This indicates that plant lodging is the main cause of the harvest loss from fallen ears in the mechanical harvesting of maize grain.

In the same test site (Tieling City, Liaoning Province), the results of harvesting in different periods (Table 3) also showed the same trend of Table 2, in which the maize lodging rate was significantly positively correlated with the loss rate of fallen ears and the total loss rate.

Table 2 Relationship between harvest loss rate and lodging rate in the mechanical harvesting of maize grain

Item	Loss rate from grain	Loss rate from fallen ears	Total loss rate	Lodging rate
Loss rate from fallen grain	1	0.364**	0.504**	−0.042
Loss rate from fallen ears		1	0.988**	0.738**
Total loss rate			1	0.350**
Lodging rate				1

Note: **: significant correlation at p<0.01 (bilateral).

Table 3 Relationship between harvest loss rate and lodging rate in the mechanical harvesting of maize grain in different periods (Tieling test site, Liaoning Province)

Item	Loss rate from fallen grain	Loss rate from fallen ears	Total loss rate	Lodging rate
Loss rate from fallen grain	1	0.346	0.443*	0.325
Loss rate from fallen ears		1	0.994**	0.983**
Total loss rate			1	0.976**
Lodging rate				1

Note: *: significant correlation at p<0.005; **: significant correlation at p<0.01 (bilateral).

The relationship between the lodging rate and the loss rate of fallen ears and the relationship between the lodging rate and the total loss rate were both found to be quadratic. The fitting equations are

$$y=0.011x^2+0.090x+2.805,\ R^2=0.598^{**} \quad (2)$$

where, y is the loss rate of fallen ears, %; x is the lodging rate, %.

$$y=0.011x^2+0.087x+4.061,\ R^2=0.530^{**} \quad (3)$$

where, y is the total loss rate and x is the lodging rate. This suggests that to achieve a total loss rate less than 3%, the lodging rate should be less than 1.78%; to achieve a total loss rate less than 5%, the lodging rate should be less than 6.1%; and to achieve a total loss rate less than 10%, the lodging rate should be less than 19.6% (Figure 5).

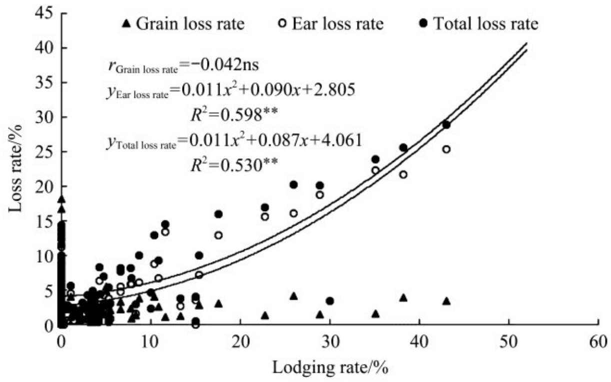
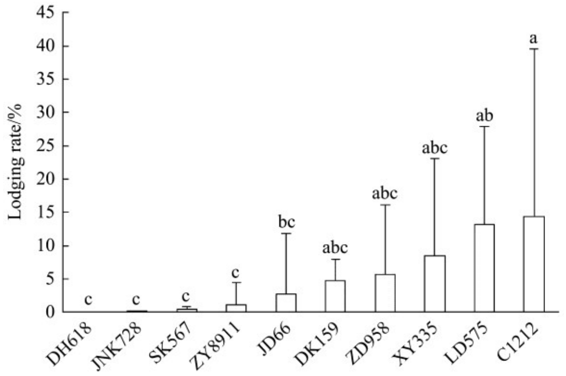


Figure 5 Relationship between harvest loss rate and lodging rate in the mechanical harvesting of maize grain

The results of the multi-point joint experiments of ten maize cultivars on harvest loss and lodging (Figure 6) showed that there were significant differences in the lodging rate at harvest among different maize cultivars. Among those maize cultivars, the average lodging rate of cultivar C1212 was 14.4%, which was significantly higher than that of the other nine cultivars. The lowest lodging rates were observed for such cultivars as DH618, JNK728, SK567, and ZY8911, indicating that there were genetic factors behind the differences in lodging rate and that the breeding of lodging-resistant cultivars could significantly reduce the harvest loss.



Note: Values followed by the same lower case letter in the same column are not significantly different at $p \leq 0.05$, according to the LSD test.

Figure 6 Differences in lodging rate at harvest among different maize varieties

Cultivar LD575 had the second-highest lodging rate of the studied cultivars (Figure 6). According to the analysis of lodging and harvest loss data (Figure 7) obtained from treatments with different plant densities (60 000 plants/hm^2, 75 000 plants/hm^2, and 90 000 plants/hm^2) and different harvest periods (10th October, 25th October, and 5th November 2019, at the Tieling test site; 11th October 2018, at the Chifeng test site; 1st October 2018, at the Liaocheng test site; and 30th September 2018, at the Ningxia test site), the results showed that, for the same cultivars, the lodging rate was highly significantly correlated with the loss rate of fallen ears, the loss rate of fallen grain, and the total loss rate, and the highest correlation was observed between the lodging rate and the loss rate of fallen ears.

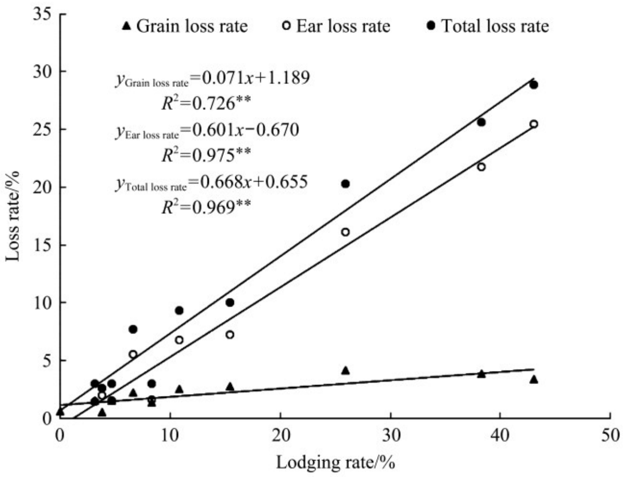


Figure 7 Relationship between the harvest loss rate and the lodging rate of cultivar LD575

3.4 Relationship between the harvest loss rate and maize plant height, ear height, and yield

The results of the multiple experiments of maize lodging and harvest loss (Table 4) showed that the plant height and ear height were both negatively correlated with the harvest loss rate of fallen grain, the harvest loss rate of fallen ears, and the total loss rate; however, only the correlations with the loss rate of fallen grain were significant. The effect of plant height and ear height on the harvest loss rate of fallen grain may be related to the contraposition of the maize header and the ear during mechanical harvesting. That is, for the cultivars with lower plant height and ear position, the maize header is more likely to directly collide with the ears when harvesting, which can cause grain breakage and higher harvest loss from fallen grains. Additionally, the grain yield was found to be negatively correlated with the harvest loss rate of fallen ears, the harvest loss rate of fallen grain, and the total harvest loss rate. Reducing harvest loss can effectively increase the actual yield in field, and a reasonable planting density can also contribute to increasing the grain yield.

Table 4 Relationships between the harvest loss rate in the mechanical harvesting of maize grain and the maize plant height, ear height, and grain yield

	Ear height	Yield	Plant density	Harvest loss rate from fallen grain	Harvest loss rate from fallen ears	Total harvest loss rate
Plant height	0.567**	0.076	0.113	−0.295**	−0.115	−0.108
Ear height	1	0.137	0.028	−0.120	−0.179	−0.146
Yield		1	0.523**	−0.435**	−0.389**	−0.251**

Note: **: significant correlation at $p<0.01$ (bilateral).

3.5 Effect of different harvesters and their operation on harvest loss

From 2012-2019, comparative tests including 35 groups of maize grain harvesters were conducted in Xinjiang Region, Gansu Province, Ningxia Province, Jilin Province, Liaoning Province, Henan Province, Anhui Province, Hebei Province and other provinces and cities in China. The variables in these experiments were harvester type, harvesting speed, cylinder rotation speed, header height, feeding amount, tail screen angle, and other operation parameters. The results (Table 5) showed that the grain moisture content at harvest ranged from 15.83%-34.36%, with an average value of 25.00%; the average total harvest loss was 255.15 kg/hm^2, which was equal to 2.01% of the average yield; the total harvest loss of all groups ranged from 102.60-515.85 kg/hm^2, corresponding to 0.33%-9.65% of the yield; the average difference between the maximum harvest loss rate and the minimum harvest loss rate was 431.1 kg/hm^2, with the largest difference being 24152.3 kg/hm^2 (the difference of harvest loss rate is 29.38%) and the minimum difference is 5.4 kg/hm^2 (the difference of harvest loss rate is 0.06%). The maximum difference between the maximum harvest loss rate and the minimum harvest loss rate occurred on 27th of September, 2019 in Yongqiao District, Suzhou City, Anhui Province, involving a test for five types of harvesters, namely Haofeng 4YZL-5, World Haolong 4LZ-7C (large), World 4LZ-5.0m, Guwang 4LZ-8B1, and Lovol Gushen GK120.

4 Discussion

Harvest losses from fallen grain and fallen ears during the mechanical harvesting of maize grain not only reduce the grain yield but also affect farmers' desire to adopt mechanical harvesting, which is an essential impediment to the promotion of the mechanical grain harvesting of maize in China. According to the statistics of 2987 groups of samples from field investigations on the quality of mechanically harvested maize grain from 2012 to 2019, the average harvest loss rate was equivalent to 3.54% of the yield. Although this value does not exceed the maximum harvest loss rate of the yield (5%), which is stipulated in the Chinese national standard[7], “Technical Requirements for Maize Combine Harvester” (GBT-21961-2008)[7], it is nevertheless higher than the maximum value of 3%, which is required by standards in the United States, Brazil, Argentina, and other European and American countries. Beyond that, there is a large difference among the harvest loss rates of studied fields, with 18.4% of the fields having a total loss rate of more than 5%. The harvest loss of maize includes two aspects: the loss from fallen grain and the loss from

Table 5 Harvest loss from fallen ears and the harvest loss from fallen grain for different harvesters and different operation parameters

Date and site of test	Cultivar	Grain moisture content/%	Average harvest loss /kg·hm^{-2}	Average harvest loss rate /%	Maximum harvest loss /kg·hm^{-2}	Minimum harvest loss /kg·hm^{-2}	Difference between harvest loss$_{Max}$ and harvest loss$_{Min}$ /kg·hm^{-2}	Harvester type	Remarks
31st, Oct. 2019 Suzhou District, Jiuquan City, Gansu Province	NH101	20.90	559.50	4.17	1084.20	146.25	937.95	Zoomlion Jiguang CB50	Header height: 79.22 cm, 61.11 cm, 84.56 cm, 107.67 cm.
		20.90	165	1.23	448.20	52.35	395.85		Tail screen angles: 0°, 22.5°, 45°, 67.5°, 90°.
		20.90	358.20	2.67	1066.65	42.90	1023.75		Forward speed: 2.5 km/h, 3.5 km/h, 5 km/h, 6 km/h, 7 km/h, 11 km/h, 13 km/h.
		20.90	430.65	3.21	1179.45	28.20	1149.90		Feeding capacity: 2 rows, 4 rows, 6 rows.
23rd, Oct. 2019 Cainiu Town, Tieling City, Liaoning Province	LD575	18.10	48.15	0.42	73.50	24.15	49.35	John Deere C110 CASE 4088	
	LD588	23.55	102.90	0.91	121.65	76.20	45.45		
4th, Oct. 2019 Lianhua Town, Wuyang County, Henan Province	JNK728	21.41	116.10	1.03	297.60	10.20	287.40	Haofeng 4YZL-5 Zoomlion 4LZ-9BZH John Deere W100 Xingguang 4YL-5 Kubota Pro108-4Y Yangzhou Jingu RG50 Lovol GM80 Boyo 4LZ-6 CASE 4088 Haofeng 4YZP-3	
30th, Sept. 2019 Lianhua Town, Wuyang County, Henan Province	JNK728	21.41	161.25	1.43	818.40	9.00	809.40	Haofeng 4YZL-5 Zoomlion TB60 John Deere W100 Xingguang 4YL-5 Kubota Pro1108-4Y Yangzhou Jingu RG50 Lovol GM80 BOYO 4LZ-6 CASE 4088 Haofeng 4YZP-3	
27th, Sept. 2019 Yongqiao District, Suzhou City, Anhui Province	ZD958	29.42	1364.85	9.65	4369.95	217.65	4152.30	Haofeng 4YZL-5 World Haolong 4LZ-7C World Haolong 4LZ-5.0m Zoomlion Guwang 8B1 Lovol Gushen GK120	
30th, Sept. 2018 Puyang City, Henan Province	NY468	23.90	211.35	2.60	222.75	199.95	22.80	Haofeng 4YZL-5 Chunyu4YZ-5CZ	
28th, Sept. 2018 Tanghe County, Henan Province	XQ829	30.13	93.15	1.84	102.30	83.55	18.75	Lovol Gushen GE50	Forward speeds: 3.87-6.32 km/h
	XQ829	32.38	169.05	3.34	208.05	122.55	85.50	Haofeng 4YZL-5	Cylinder rotation speed: 540-590 r/min
	DH618	26.29	176.25	2.75	203.70	149.25	53.85	Haofeng 4YZL-5 Lovol Gushen GE40	
23rd, Sept. 2018 Lianhua Town Wuyang County, Henan Province	DK517	24.13	426.00	4.09	906.15	100.05	806.10	Haofeng 4LZ-8.0 Zoomlion Guwang TB60	Forward speed: 1.66-5.72 km/h Forward speed: 1.49-8.38 km/h
	DK517	23.54	338.55	3.25	576.00	160.35	415.50	Haofeng 4LZ-8.0	Cylinder rotation speed: 540-1000 r/min
28th, Sept. 2017 Shenqiao Town Zhecheng County, Henan Province	KY186	22.00	330.00	4.00	460.80	460.80	460.80	HuaSeng 4YB-4 Xiyingying 4YB-4 Shifengjinying 4LZ-2	
4th, Nov. 2016 Dongbatou Town Lankao County, Henan Province	SD636	31.64	134.25	1.50	219.30	50.10	169.20	CASE 4088 Lovol Gushen GE50	
	JNK728	28.20	423.00	0.38	45.00	52.05	40.20		
	DK517	28.15	422.25	0.71	93.15	156.15	55.05		
	JNK728	28.05	46.20	0.39	52.05	40.20	11.85	CASE 4088	Forward speed: 4.46 km/h, 6.95 km/h
	DK517	28.39	106.35	0.81	156.15	55.05	101.10	CASE 4088	Forward speed: 6.12 km/h, 9.03 km/h

Date and site of test	Cultivar	Grain moisture content/%	Average harvest loss /kg·hm^{-2}	Average harvest loss rate /%	Maximum harvest loss /kg·hm^{-2}	Minimum harvest loss /kg·hm^{-2}	Difference between harvest loss$_{Max}$ and harvest loss$_{Min}$ /kg·hm^{-2}	Harvester type	Remarks
3rd, Oct. 2016 Lilin Town, Jiyuan City, Henan Province	HX118	31.20	270.90	2.98	273.60	268.05	5.40	Zoomlion 4YZL-5B Xiyingying4YB-4 Zoomlion GuwangTB604	
10th, Oct. 2015 Cizhou Twon, Ci County, Hebei Province	BY721	27.10	45.45	0.46	59.25	31.65	27.75	Dongfeng E5184YZ-6 ZoomlionGuwanTB604	
4th, Oct. 2015 Linying County, Henan Province	NY721	33.10	87.15	0.82	97.80	75.45	22.35	Lovol GushenGE50	Forward speed: 3 km/h, 5 km/h
30th, Nov. 2015 Ninghua Village Yongning County, Ningxia Province	DK519	29.39	218.55	1.39	363.15	108.45	253.05	Lovol Gushen GF604YL-5F Lovol Gushen GF604YL-4E1 Lovol Gushen GK1004YL-6K Huashenghoude 4YZ-5	
29th, Sept. 2015 Linying County, Henan Province	ZZ 8	25.97	118.20	0.96	176.10	40.65	136.65	Lovol Gushen GF604YL-4	Eight different harvesters of same type
23rd, Oct. 2014 Heilinzi Town, Gongzhuling City, Jilin Province	NH101	23.03	76.20	0.48	81.00	69.90	11.10	Dongfeng E518 John Deere C110	
30th, Nov. 2014 Xinji County, Hebei Province	HM 1	34.36	118.20	0.89	195.30	39.90	155.40	Lovol Gushen GE50 Boyo 4LZ-6	Forward speed: 3 km/h Forward speed: 5 km/h
10th, Oct. 2012 Taxiu Town, Wenquan County, XUAR	KWS2564	26.45	143.40	0.80	243.90	46.65	197.25	Dongfeng E514 John Deere 1076	
10th, Oct. 2012 HajibuhuTown, Wenquan County, XUAR	DMY1	17.05	302.70	2.81	344.70	261.75	82.95	John Deere 1075 John Deere 1076	
	KWS2564	24.44	155.10	0.92	767.25	18.60	748.80	John Deere W210 John Deere 1075 John Deere 1076 Dongfeng E514 Dongfeng E516, John Deere C230	
	KX3564	24.47	57.15	0.33	78.00	15.60	62.40	John Deere W210 Dongfeng E514 John Deere 1075	
10th, Oct. 2012 71st Farm, Xinyuan County, XPCC	XY335	15.83	113.10	0.65	141.00	83.55	57.45	Dongfeng E518 John Deere 1075	
	XY335	19.40	950.55	5.74	2212.35	264.90	1947.45	John Deere1076 John Deere 3316 (Now known as C100)	
	KX1568	19.09	88.05	0.57	316.95	29.40	287.55	John Deere 1075 Dongfeng E518 Dongfeng E514	
Average		25.00	255.15	2.01	515.85	102.60	431.10		

Note: XAR: Xinjiang Uygur Autonomous Region; XPCC: Xinjiang Production and Construction Corps.

fallen ears. The results of this study show that the average harvest loss from fallen grain and the average harvest loss from fallen ears account for 23.5% and 76.5% of the average total harvest loss, respectively. That is, the average harvest loss from fallen ears is 3.2 times as much as the average harvest loss from fallen grain, which indicates that the harvest loss in the mechanical harvesting of maize grain mainly matters that from fallen ears. This finding is similar to the results of Smith[11,33].

In this study, 14 tests were conducted at 11 experimental sites from 2018 to 2019. The results for multiple harvest periods and studies of the same maize cultivar at different test sites showed that the plant lodging rate (root lodging and stem breakdown) was significantly positively correlated with the ear falling rate and the total harvest loss rate, and that ear falling caused by lodging was the main cause of harvest loss. Among them, the fitting equations were as follows:

$$y_{\text{ear falling rate}}=0.011x^2+0.090x+2.805,\ R^2=0.598^{**} \quad (4)$$

$$y_{\text{total harvest loss rate}}=0.011x^2+0.087x+4.061,\ R^2=0.530^{**} \quad (5)$$

where, x is the plant lodging rate. These findings suggest that, in order to achieve a total harvest loss rate of less than 3%, the lodging rate should be less than 1.78%, and to achieve a total harvest loss rate of less than 5%, the lodging rate should be less than 6.1%. The harvest loss caused by lodging mainly occurs before harvesting, and there are great differences in lodging resistance among maize cultivars. Therefore, it is important to select maize varieties of high lodging resistance in the later growth period, adopt reasonable planting densities, cultivate healthy plants, and to harvest at an appropriate time. These suggestions are discussed in detail as follows.

4.1 Breeding of lodging-resistant varieties

In the past, China's maize harvesting was mainly performed manually or by mechanical ear picking. Maize breeders did not pay enough attention to the lodging resistance of cultivars in the dehydration stage after its physiological maturity, and there has been little research on the introduction and breeding of lodging-resistant cultivars. In the future, it is necessary to concentrate on the breeding of cultivars of high lodging resistance, especially the lodging resistance during the dehydration period after its physiological maturity.

4.2 Disease prevention, pest control, and healthy cultivation

If the growth of maize plants is weak, maize borer and stem rot will cause plant lodging, stalk breakage, and ear falling, which will not only take place harvest loss but also seriously affect the quality and efficiency of maize grain's mechanical harvesting. Therefore, enhancing the prevention and control of maize stem rot, maize borer, ear rot, and other diseases and insect pests, adopting reasonable planting densities and adaptive irrigation and fertilization management, using special growth regulators to control maize plant height, and ensuring the healthy and strong growth of maize plants, are beneficial to reducing the harvest loss.

4.3 Harvest at the appropriate time

The results of this study showed that the harvest loss rate of fallen grain was the lowest when the grain moisture content ranged from 25% to 30%, and the harvest loss rate of fallen ears was generally lower for grain moisture contents of 20%-40%. However, when the grain moisture content was lower than 20%, the loss rate of fallen grain, the loss rate of fallen ears, and the total loss rate all increased significantly with a decreasing grain moisture content (i.e., with the delay of harvesting time). Therefore, harvesting at an appropriate time could effectively reduce the risk of lodging, loss from fallen ears, and loss from fallen grain during the mechanical harvesting of maize grain. According to Piggott[25], when the moisture content of maize grain is 26%-29%, natural grain falling is only equivalent to 1% of the yield, and when the grain moisture content drops below 25%, the natural grain falling rapidly increases to around 10% of the yield[25]. In production, an appropriate time for harvesting could be estimated by measuring the grain moisture content and the lodging risk.

Additionally, the results of this study also showed that the type of harvester and the harvester operation parameters both affected the harvest loss in field. Different types of harvesters and different harvesters of the same type will cause different harvest losses in field. In this study, based on the results of 35 groups of comparative tests of harvester operation, it was shown that the average difference between the maximum and minimum harvest loss rates among different types of harvesters and various operation parameters was 431.1 kg/hm^2, and the harvest losses ranged from 102.60-515.85 kg/hm^2, corresponding to 0.33%-9.65% of the yield. According to previous studies[30,34-36], the cause of harvest loss in the process of mechanical harvesting of maize grain includes the fallen ears and fallen grain resulting from ear collection, incomplete shelling or inadequate cleaning of the threshing, and separating device. Furthermore, some grain will be broken during ear-picking and grain-threshing[37,38]. Additionally, the difference in harvest loss among different harvesters of the same type is related to the threshing drum speed, screen clearance, fan speed, and operation mode. Therefore, in addition to promoting the development of harvesting machinery with lower grain breakage rate and less harvest loss, it is necessary to consider the applicable harvester[39], maize cultivars[40,41], planting density, plant spacing and row spacing[10,42-44], plant diseases and insect pests[40,41], yield, grain moisture content, lodging rate, weather conditions during harvesting[45-47], the terrain conditions of fields[48], and the adjustment of harvester operation parameters, all of which can significantly reduce the harvest loss.

5 Conclusions

In this study, the analysis of mechanically harvested maize grain samples, obtained in field from 2012 to 2019 and divided into 2987 groups, showed that the total harvest loss rate in mechanical harvesting of maize grain is equal to 3.54% of the yield, with the loss from fallen ears being 3.2 times as much as the loss from fallen grain. Besides, the results showed that, firstly, the harvest loss rate of fallen grain is the lowest when the grain moisture content at harvesting maintains in the range of 25%-30%; secondly, the harvest loss rate of fallen ears is lower when the grain moisture content maintains in the range of 20%-40%; and thirdly, when the grain moisture content is lower than 20%, the harvest loss rate of fallen ears, the harvest loss rate of fallen grain, and the total harvest loss rate increase rapidly with a decreasing grain moisture content (i.e., with the delay of harvesting time). Furthermore, it is found that the lodging rate is significantly positively correlated with the harvest loss rate of fallen ears and the total harvest loss rate. The loss from fallen ears caused by lodging is the main cause of the harvest loss, and it is also found that, in order to achieve a total harvest loss rate of less than 5%, the lodging rate should be less than 6.1%. Moreover, based on comparative tests of 35 groups of harvester during the mechanical harvesting of maize grain, it is shown that the average difference between the maximum harvest loss and minimum harvest loss among different types of harvesters and various operation parameters is 431.1 kg/hm^2, with a range of 102.60-515.85 kg/hm^2, equivalent to 0.33%-9.65% of the yield. The results of this study suggest that the major paths to reduce the harvest loss in mechanical harvesting of maize grain are the breeding of maize cultivars that are resistant to lodging in the late stage of growth, the adoption of reasonable planting densities, the cultivation of healthy and strong plants, the development of harvesters with lower harvest loss, the intensification of operator training, and the estimation of an appropriate harvest time.

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