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Study on Performance Improvement of a Head-Feeding Rice Combine for Foxtail Millet Harvesting

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Abstract

Purpose: The study was conducted to investigate the proper working conditions like the mesh size of the concave and the chaffer angle of the oscillating sieve, and the fan speed of the head-feeding rice combine for foxtail millet harvesting. **Methods:** The study aimed to determine the harvesting conditions for the rice combine harvester at a 0.5 m/s working speed and at 40° and 55° sieve chaffer angles. The harvesting loss of the foxtail millet based on the speed of the fan and the oscillating speed of the sieve was measured at three levels of fan speed and oscillating sieve speed. **Results:** The threshing rates of different foxtail millet varieties were 64.1~83.5% at a mesh size of 7 mm of the concave. In experimental foxtail millet harvesting, the optimal operating condition of the rice combine harvester included a 40° sieve chaffer angle and a 4.8 Hz oscillating sieve (cleaning shoe) frequency. The grain loss was found to be lower at a 40° than at a 55° sieve chaffer angle. In field harvesting using the combine harvester, the lowest harvesting grain loss rate of the foxtail millet varieties ranged between 0.2~0.5% at a 7 mm mesh concave, 40° chaffer angle, 4.8 Hz sieve frequency, and a 20 m/s fan speed at an engine speed of 2,000 revolutions per minute (RPM). **Conclusions:** Findings showed that foxtail millet could be harvested using the combine harvester.

Keywords: Cleaning, Combine harvesters, Concaves, Millets, Threshing

Introduction

Foxtail millet is one of the cereal crops grown in 1,100 ha in Korea (COSIS, 2009). Harvesting of foxtail millet is not mechanized and is usually conducted manually requiring more labor inputs. However, lately, foxtail millet is becoming known as a food material with an increasing consumption that is mostly available through imports.

Agricultural labor in rural areas of Korea is minimal, thereby leading to increased labor costs and difficulties in finding the required labor workers. To solve this problem, mechanization of harvesting the foxtail millet is required.

In Korea, rice cultivation is common and the combine harvester is readily available for rice harvesting in large numbers. Foxtail millet is similar to rice in terms of the crop height, crop shape, and the harvesting method. Thus, a head-feeding combine harvester for rice is adaptable to foxtail millet harvesting. Moreover, there is no problem in its use because harvesting of foxtail millet is done after rice. In the case of harvesting foxtail millet using the combine harvester, labor inputs can be reduced and its usage rate can be enhanced (Jun et al., 2014).

Balasubramanian and Viswanathan (2010) reported the physical properties of foxtail millet in 1,000 kernel weight, bulk density, true density, porosity, angle of repose, coefficient of static friction, coefficient of internal friction, and grain hardness. The method of harvesting the foxtail millet is similar to that for rice but its grain properties are very different from rice.

Thus, a study on mechanical harvesting of foxtail millet through threshing and selection of foxtail millet is deemed necessary. Grains of foxtail millet usually separate into grain and small cluster grains during threshing. This is

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because the heads of the foxtail millet consist of cluster grains. There are significant losses of grain during the cleaning process because it is difficult to separate the clustered and wrapped grains because their sizes are very small.

Therefore, this study was conducted to investigate threshing, separation, and cleaning of the foxtail millet.

Materials and Methods

Samples of foxtail millet for experiment

Test samples of Millet I (big grain), Millet II (small grain), and the crop properties of each sample were investigated. Table 1 shows the properties of the foxtail millet samples, while Figure 1 shows the size and shape of the foxtail millet crop.

Experiment 1: Threshing performance of threshing device concaves

For the improvement of the threshing performance of the foxtail millets, a threshing device was designed (Figure 2). Its size was designed to be the same as the size of the threshing device of the rice combine harvester (Model-DSM70). In the threshing part of the device, the number of rotations can be adjusted and the size of the concave opening can be changed for the performance test. Two millet varieties (Table 1) were used for the threshing test.

Table 1. Properties of the foxtail millet samples

Variety	Total height (m)	Length / Diameter of millet head (mm)	Diameter of grain (mm)	Diameter of clustered grain (mm)	Weight (g / 1000 grains)	Moisture content (dry base) of millet head (%)
Millet I (Hwanggeum)	1.13	127 / 20	2.1	10	3.1	24.5
Millet II (Samdachal)	1.27	170 / 18	1.8	9	2.7	24.5

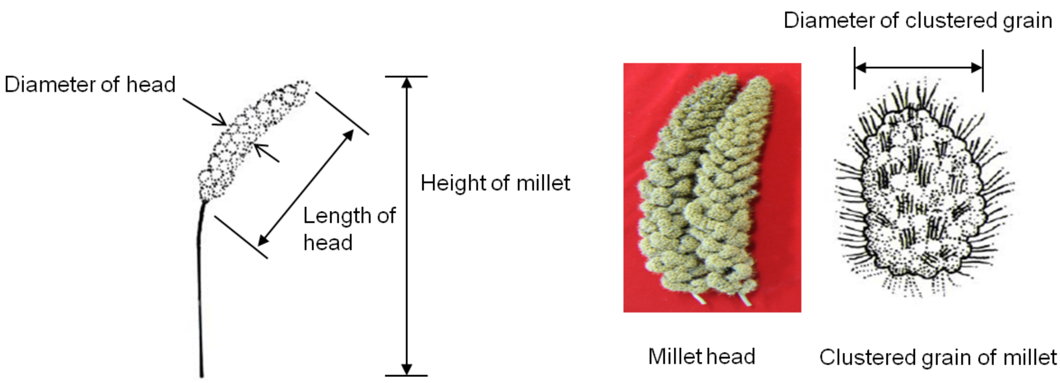


Figure 1. Size measurement and shape of foxtail millet crop.

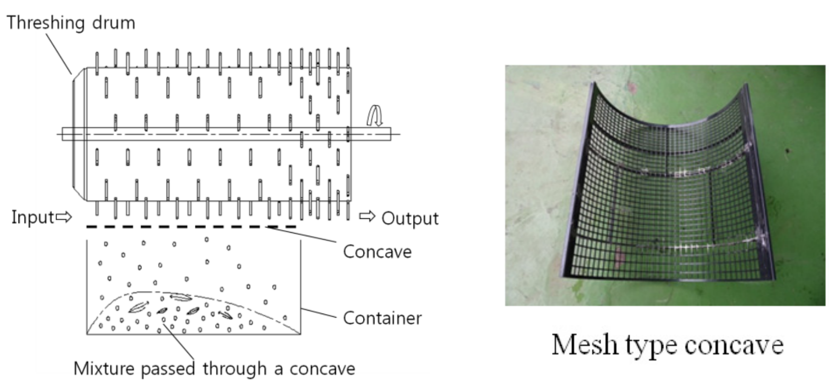


Figure 2. Schematic diagram of the threshing device used for the conducted experiments for the threshing performance of concaves.

Table 2. Experimental conditions of the threshing device

Variety	Opening size of concave (mm)	Diameter of threshing drum (mm)	RPM and peripheral speed of threshing drum [RPM / (m/s)]
Two samples [Millet I (Hwanggeum), Millet II (Samdachal)]	Four levels (5×5, 7×7, 10×10, 18×18)	560	500 / 14.6

The speed of the threshing drum of the combine harvester was fixed at maximum 500 revolutions per minute (RPM) for rice (Tarui, 1962).

As shown in Table 1, the diameter of the clustered grain of the foxtail millet ranged between 9~10 mm. To thresh the clustered grain, the opening size of the concave mesh needed to be under the minimum of 10 mm. In addition, the straw of the millet was cut and input to the threshing drum. It was then threshed with the head of the grain because the straw of the millet was not tougher than rice. Therefore, it was considered that the 18 mm of opening size of the concave mesh used for rice was also included for the threshing experiment of the millets.

Threshing experiments of the millet samples were conducted using four concave types with opening sizes of 5 mm × 5 mm, 7 mm × 7 mm, 10 mm × 10 mm, and 18 mm × 18 mm. For the status of the threshed millets using the threshing device, the rates of grains, clustered grains, and stems of the collected millet samples-which passed through the concave opening-were investigated. Table 2 shows the experimental conditions of the threshing device.

Experiment 2: Measurement of the experimental grain loss at the cleaning sieve of the combine harvester

A threshing test of the millet was conducted using the rice combine harvester (Model-DSM70) during threshing, separating, and cleaning (Figure 3). Table 3 shows the parameters of the tested head-feed rice combine harvester. In the separation test of the millets, removing the threshing part and changes of the chaffer angle, frequency of the cleaning sieve, and rotating speed of the fan were conducted in the rice combine harvester. Table 4 shows the experimental conditions for the measurement of the grain loss of the foxtail millet at the separation part and cleaning sieve of the combine harvester. To decrease grain loss and enhance quality of harvested grains, it is important to consider the factors of threshing, separation, and cleaning, which include the threshing concave, chaffer angle, sieve frequency, and air velocity. As shown in Table

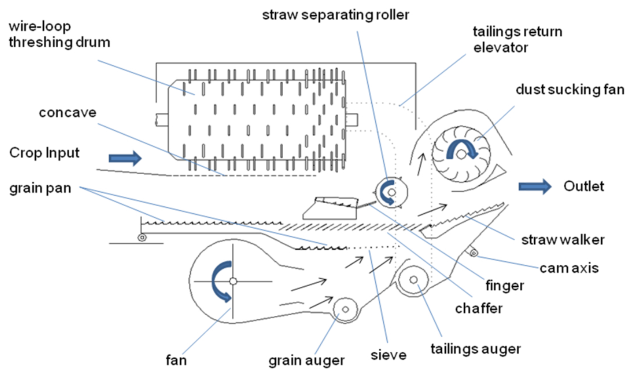


Figure 3. Schematic diagram of the threshing unit and cleaning shoe of the head-feeding type of the rice combine harvester (DSM70).

3 and Figure 4, the combine harvester has three levels of fan speed that can be adjusted via the lever position, and the frequency of the cleaning sieve (shoe) that works in proportion to engine speed. The working speed for the experiment conducted in the field was set at all three levels. For an engine speed of 2000 RPM, the combine harvester can barely operate at a working speed of 0.5 m/s. The engine speed can reach a maximum of 3,000 rpm.

Generally, the grain of rice is not heavier than barley and wheat. Nevertheless, the rice straw is tougher than barley and wheat straw. The chaffer angle of the rice combine harvester was set at 35° for rice and at 45° for barley. Therefore, the chaffer angle of the cleaning sieve for the foxtail millet harvesting experiment was set at the two levels of 40° and 55° to delay the time required for the foxtail millet straw to go through the chaffer sieve for the separation, as shown in Figure 5. This is because the foxtail millet straw is not tougher than rice but easily broken. For the grain loss experiment of the foxtail millet in the field, the choice of 5 mm as the opening size of the concave mesh was excluded because the amount of threshed grain was small and many clustered grains were discharged together with straw exiting the outlet of the combine cleaning sieve (shoe).

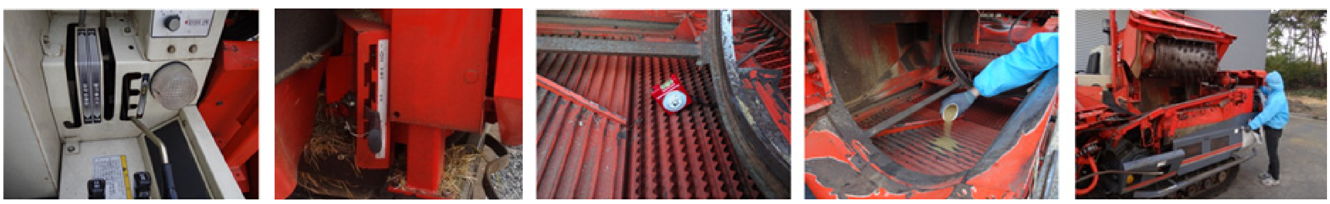
The study was conducted using two types of grain (grains, clustered grains) of the Millet samples, at three

Table 3. Parameters of the head-feeding type for the rice combine harvester

Parameters of the rice combine harvester		Value
Engine	Power/Speed (kW/RPM)	48 / 2,700
Cutting part	Cutting width (mm)	1,450 – 1,500
	Cutting Height (mm)	35 – 150
	Adaptable height of crop (mm)	550 – 1,300
Threshing part	Length of threshing drum (mm)	900
	Diameter of drum (mm)	550
	RPM of drum (rpm)	505
	Opening of concave (mm)	7 × 7 – 18 × 18
Separation and cleaning part	Length and width of cleaning shoe (mm)	665 × 1,550
	Amplitude of cleaning shoe (mm)	20
	Frequency of cleaning shoe (Hz)	4.8 – 7.2
	Adjusting chaffer angle of cleaning shoe (°)	25 – 55
Fan	Number of fan wings	4
	Length of fan (mm)	690
	Diameter of fan (mm)	340
	Speed of fan (three levels) (RPM)	755 – 1,622

Table 4. Experimental conditions for the measurement of the grain loss of the foxtail millet at the separation part and the cleaning sieve of the combine harvester

Parameters	Contents
Variety of foxtail millet	Millet II (Samdachal)
Weight of sample (g / time)	Two levels (pure grain:100g, clustered grain:50 g)
Frequency of cleaning shoe (Hz)	Three levels (4.8, 6.1, 7.2)
Position of fan adjustable lever	Three levels (high, middle, low)
Chaffer angle of the sieve (°)	Two levels (40, 55)



Fan adjusting · Chaffer adjusting · Chaffer · Sample input · Lossed grain collecting

Figure 4. Experimental equipment and testing method used for grain loss measurement.

fan speed levels (high, middle, and low), at three oscillating frequency levels (4.8 Hz, 6.1 Hz, 7.2 Hz), and two chaffer angles (40°, 55°) of the sieve. Samples of grains and clustered grains, weighing 100 g and 50 g, respectively, were examined separately. The rate of grain loss at the outlet of the cleaning shoe, as shown in Figure 3, was calculated using the following equation(1):

Grain loss rate (%) = (weight of grains at outlet of cleaning shoe/weight of input grains)×100 (1)

Figure 3 shows the schematic diagram of a threshing unit and the cleaning shoe of the head-feeding rice combine harvester (DSM70). Table 4 presents the experimental conditions for the measurement of the grain loss of the foxtail millet at the separation part and at the cleaning sieve of the combine harvester. Figure 4 presents the experimental equipment and the method for the testing

Table 5. Operating conditions of the combine harvester according to the adjustable lever position

Speed of engine (RPM)	RPM and peripheral speed of wire-loop threshing drum [RPM / (m/s)]	Frequency of cleaning shoe (sieve) (Hz)	Peripheral and rotating speed of fan (Φ=340 mm) by adjusting the lever position [(m/s) / RPM]		
			High	Middle	Low
2,000	352 / 10.3	4.8	20 / 1,123	15 / 869	13 / 757
2,500	443 / 13.0	6.1	25 / 1,378	19 / 1,074	17 / 937
3,000	532 / 15.6	7.2	29 / 1,622	23 / 1,280	20 / 1,119

Table 6. Sieve chaffer dimension of the rice combine harvester

Parameter	Unit	Value
Chaffer width (W)	mm	695
Full length of chaffer (L)	mm	600
Range of chaffer angle	°	25–55
a1	mm	20
a2	mm	10
b1	mm	23
b2	mm	43
b3	mm	53

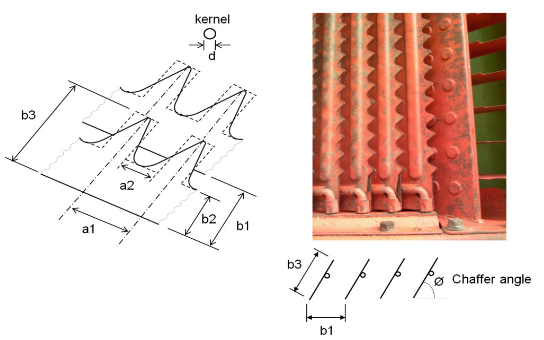


Figure 5. (a) Geometry of chaffer surface. The dotted line indicates the approximate outline of the chaffer vanes of the rice combine harvester. (b) The shape of the chaffer of the combine harvester (DSM70).

of grain loss at the separated parts of the combine harvester. Table 5 shows the speed of the air fan of the combine harvester based on the adjustable position. Table 6 shows the chaffer dimensions, while Figure 5 presents the geometry of the chaffer surface (Srivastava and Carroll, 1991; Srivastava et al., 2006) and the shape of the chaffer of the combine harvester (DSM70).

Experiment 3: Measurement of the harvesting grain loss of the foxtail millet using the combine harvester in the field

Foxtail millets were planted in the test field based on a cultivation style with a 1.5 m bed width and a 1.2 m planted width. The rice combine harvester (Model-DSM70) was used for the millet harvesting experiments. The rice combine harvesting process consisted of the cutting, transporting, threshing, separation, cleaning, collecting and discharging processes, and the driving part. The cutting width of the combine was 1.4 m and the length of the crops for ideal threshing ranged between 0.55~1.3 m. In order to measure the grain loss while harvesting, the length of the test bed per time was 3 m, and the grains and straw were collected at the outlet of the cleaning shoe of the combine harvester. The combine harvesting test was conducted with two types of millets (Millet I and Millet II). The experimental factors were the three levels of the concave opening size (7 mm, 10 mm, and 18 mm), the three levels of the sieve oscillating frequency (4.8 Hz, 6.1 Hz, and 7.2 Hz), and the two levels of the chaffer angle (40° and 55°). The working speed was 0.5 m/s and the air fan speed was set to a low value using the adjustable lever position. The chaffer angle of the cleaning shoe was measured horizontally and the loss of the grain was calculated using the following equation(2):

$$\text{Grain loss rate (\%)} = (\text{loss of grain at outlet of cleaning shoe/average grain of each test bed}) \times 100 \qquad (2)$$

Table 7 shows the parameters used for measuring the harvesting grain loss of the foxtail millet in the field, while

Table 7. Experimental conditions for measuring the harvesting grain loss of foxtail millet in the field

Variety of foxtail millet	Cutting width of the combine (m)	Testing length (m/time)	Opening size of concave mesh (mm)	Chaffer angle of sieve (°)	Working speed (m/s)
Two samples [Millet I (Hwanggeum), Millet II (Samdachal)]	1.4	3	Three levels (7×7, 10×10, 18×18)	Two levels (40, 55)	0.5

Millet harvesting | Lossed grain collecting | Chaffer adjusting lever

Figure 6. Experimental method for grain loss testing in field using the combine harvester.

Figure 6 shows the measure of the grain loss using the combine harvester.

Results and Discussion

Threshing performance of concaves in the threshing device

Table 8 shows the distribution of the foxtail millet that passed through the mesh concave of the threshing device. For the two millet types studied, the rate with which the pure grain of the foxtail millet mixture passed through the mesh concave ranged from 86.2~92.4% at an opening size of the mesh concave of 5 mm × 5 mm. The rate of pure grain reduced as the opening size of the mesh concave increased. However, as shown in Figure 7, the amount of the threshed grain was smallest at an opening size of the mesh concave of 5 mm × 5 mm, and caused a significant grain loss when the millet straw was discharged with clustered grain in the outlet of the combine harvester. For an opening size of the mesh concave of 18 mm × 18 mm, the rate of the pure grain loss ranged from 28.5~54.5%. Likewise, in both millet varieties, the clustered grain increased as the opening size of the mesh concave was increased. In a similar manner, the amount of straw largely increased at a mesh concave opening size of 18 mm × 18 mm.

Grain loss at the cleaning shoe of the combine harvester

Table 9 shows the grain loss rate of pure grain and

Table 8. Distribution of the mixture of foxtail millet that passed through the mesh concave after threshing

Variety	Opening size of mesh concaves (mm)	Distribution of threshed foxtail millet component that passed through the mesh concave (%)		
		Pure grain	Clustered grain	Straw
Millet I (Hwanggeum)	5×5	92.4	7.3	0.3
	7×7	83.5	16.3	0.2
	10×10	60.6	39.1	0.3
	18×18	54.5	44.7	0.8
Millet II (Samdachal)	5×5	86.2	13.3	0.5
	7×7	64.1	35.5	0.4
	10×10	60.2	39.5	0.3
	18×18	28.5	67.6	3.9

5 mm × 5 mm | 7 mm × 7 mm | 10 mm × 10 mm | 18 mm × 18 mm

Figure 7. Mixture of foxtail millet that passed through the concave mesh after threshing.

Table 9. Grain loss rate of the foxtail millet as a function of the adjustable air fan position

Chaffer angle of sieve (°)	Engine speed (RPM)	Frequency of cleaning shoe (Hz)	Loss rate of the samples of foxtail millet as a function of the adjustable air fan position (%)					
			Sample of pure grain			Sample of clustered grain		
			High	Middle	Low	High	Middle	Low
40	2,000	4.8	6.0	0.8	0.9	6.0	1.0	0.3
	2,500	6.1	7.8	3.9	1.6	13.2	4.2	2.0
	3,000	7.2	14.6	12.6	5.0	22.0	7.4	4.6
55	2,000	4.8	8.1	1.2	1.1	8.2	2.4	0.6
	2,500	6.1	8.6	4.2	1.9	6.4	7.0	4.0
	3,000	7.2	15.2	12.1	6.5	13.8	11.6	9.4

Table 10. Grain loss rate based on engine speed and sieve chaffer angle at the outlet of the sieve

Size of concave mesh (mm)	Variety of foxtail millet	Grain loss rate at the outlet of the sieve according to sieve frequency and chaffer angle (%)					
		4.8 Hz (fan speed=13 m/s, engine 2,000 RPM)		6.1 Hz (fan speed=17 m/s, engine 2,500 RPM)		7.2 Hz (fan speed=20 m/s, engine 3,000 RPM)	
		40°	55°	40°	55°	40°	55°
7 × 7	Millet I	0.2	1.6	3.7	12.6	2.6	9.6
	Millet II	0.5	2.3	4.4	14.6	3.1	13.8
10 × 10	Millet I	0.3	1.3	5.3	15.6	3.7	15.7
	Millet II	3.3	3.5	25.7	32.4	33.8	36.1
18 × 18	Millet I	2.0	4.0	7.9	0.6	9.6	5.0
	Millet II	3.3	-	42	-	35.3	-

clustered grain at different levels of the chaffer angle and at different fan frequencies. In each test, pure grain and clustered grain were used, as shown in Table 3. The grain loss rate was 0.9% for pure grain and 0.3% for clustered grain at a chaffer angle of 40°, at a cleaning shoe frequency of 4.8 Hz, and for a low-level position of the fan adjusting lever. At a chaffer angle of 55°, a cleaning shoe frequency of 4.8 Hz, and a low-level position of the fan adjusting lever, the grain loss rate was 1.1% for pure grain and 0.6% for clustered grain. However, as the frequency of the cleaning shoe and the fan lever position increased, the grain loss rate increased as high as 14.6% for pure grain and 22.0% for clustered grain at a chaffer angle of 40°. Correspondingly, at a chaffer angle of 55°, the grain loss rate results were 15.2% and 13.8% for pure and clustered grains, respectively.

Results showed that the main factors contributing to grain loss upon operation of the combine harvester were the frequency of the cleaning shoe and the RPM of the fan, for each chaffer angle of the cleaning shoe. However, a study on the determination of the main factors affecting threshing and cleaning is important for combine harvesting in fields because grain and straw of millets are put together into the threshing device.

Moreover, the terminal velocity (Vt) of the millet was calculated using the following equation(3), which is based on the rate of the moisture contents (W) of the millet (Silva et al., 2003).

$$Vt = 0.0498W + 2.0551 \tag{3}$$

Vt = Terminal velocity of millet (m/s)
W = Moisture content (%) on dry base

Based on the equation, the terminal velocity of the millet ranged from 2.6~3.6 m/s at 8~32% moisture content of the millet.

Grain loss of foxtail millet using the combine harvester in the field

Table 10 shows the loss grain rate at the outlet of cleaning shoe of the combine harvester for two varieties of millet. The grain loss rate ranged from 0.2~0.5% at a 7 mm × 7 mm concave opening size of the threshing device, a 4.8 Hz oscillating sieve frequency of the cleaning shoe device, and a 40°chaffer angle. The grain loss rate subsequently increased to 1.6~2.3% at a 55° chaffer angle. The grain loss rate also increased at chaffer angles of 40°

Figure 8. Working condition of head-feeding rice combine harvester used in harvesting the foxtail millet.

and 55° as the frequency of the sieve (cleaning shoe) increased. At a concave opening size of 18 mm × 18 mm, a 4.8 Hz oscillating sieve (cleaning shoe) frequency, and a 40° chaffer angle, results yielded a 2.0~3.3% grain loss rate. However, at a 55°chaffer angle, the separation and cleaning work became impossible because many stems and clustered grains passed through the concave. It was impossible to separate and clean the stems and clustered grains at the cleaning shoe. These were not conveyed into the tailings return elevator by the auger and then discharged to the outlet of cleaning shoe of the combine harvester. Figure 8 shows the head-feeding type for the rice combine harvester being used in harvesting the foxtail millet.

Conclusions

The study was conducted to investigate the different mesh sizes of the concave, chaffer angles of the oscillating sieve, and the air fan speed of the head-feeding type for the rice combine harvester used for harvesting the foxtail millet in the field. The harvesting conditions were investigated at a working speed of 0.5 m/s and at each sieve chaffer angle set at 40° and 55° for the rice combine harvester. Threshing rates of foxtail millet varieties were 64.1~83.5% at a 7 mm mesh size of the concave. The loss rate of the foxtail millet was 0.9% at a 40° sieve chaffer angle and at a 4.8 Hz oscillating sieve (cleaning shoe) frequency. In the field, optimal operating conditions were attained for the combine harvester given that the lowest harvesting grain loss rate of the foxtail millet varieties ranged between 0.2~0.5% at a 7 mm mesh concave, a 40° chaffer angle for the sieve, a 13 m/s fan speed, and at a 4.8 Hz sieve frequency at 2,000 RPM of engine speed. Findings showed that it was possible to harvest the foxtail millet using the combine harvester and reduce labor costs and harvesting time, thereby extending the uses of the head-feeding rice combine harvester.

Conflicts of Interest

The authors have no conflicting financial or other interests.

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