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Harvesting Performance of the Prototype Small Combine for Buckwheat and Adlay

Soonam Yoo[1], Changhoon Lee[1], Beom Seob Lee[2]*, Young Tae Yun[3]

[1]Department of Rural & Bio-systems Engineering, Chonnam National University, Gwangju 61186, Republic of Korea
[2]Ofe Co. Ltd., Kyoungnam 52007, Republic of Korea
[3]National Academy of Agricultural Science, Rural Development of Administration, Jeonju 54875, Republic of Korea

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Abstract

Purpose: The aim of this study was to investigate the harvesting performance of a prototype small combine for buckwheat and adlay. **Methods:** The prototype small combine was designed and constructed. Its ratio of grain loss, ratio of output components in the grain outlet, and field capacity for harvesting buckwheat and adlay were analyzed through field tests. **Results:** The prototype small combine required a working width of about 0.6 to 0.7 m to harvest buckwheat. The maximum travel speed was about 0.36 m/. The total ratio of grain loss was about 21.6%, which consisted of 8.8% at the header and 12.8% at the dust outlet. The grain and the material other than grain (MOG) ratios at the grain outlet were 94.1% and 5.9% respectively. In the case of adlay harvest, the maximum working width was about 1.2 m, that is, two rows. The range of maximum travel speed was about 0.45 to 0.46 m/s. When adlay was harvested in one row, the total ratio of grain loss ranged from 36.3 to 42.8% according to the cutting height. The cutting height of 30 cm resulted in a higher total ratio of grain loss than 60 cm and 90 cm. When the cutting height was 60 cm, there was no significant change in the total ratio of grain loss according to the number of working rows and the stage of the primary transmission shift. The total ratio of grain loss ranged from 35.2 to 37.7%. The grain and the MOG ratios at the grain outlet ranged from 93.1 to 95.8% and from 4.2 to 6.9%, respectively. No significant difference was observed in relation to cutting height, number of working rows, and the stage of the primary transmission shift. **Conclusions:** The prototype small combine for harvesting miscellaneous cereal crops showed good potential for the efficient harvesting of buckwheat and adlay. However, to improve the harvesting performance, there seems to be a need to develop new crop varieties suitable for machine-based harvesting and improve the transmissions, reels, separation/cleaning systems.

Keywords: Buckwheat and adlay, Harvesting performance, Prototype small combine

Introduction

In South Korea, the demand for high acre-value crops like buckwheat and adlay is on the rise as they have been recognized to be good for health. The majority of these crops are cultivated by small family farms in semi-mountainous areas. Although some farms use cutting or threshing machines during harvest, most of the process depends on a senior or female workforce. Some large and middle-sized conventional multi-purpose combines, which have been released on the market, are being considered to mechanize the harvest of these crops. However, they seem to be inappropriate for small family farms mainly run by senior or female residents because of land conditions, workforce type, harvesting performance for buckwheat and adlay, and excessive cost of the machines. Accordingly, it is very urgent to develop a small efficient and inexpensive combine harvester that is especially suitable to harvest miscellaneous cereal crops on small farms.

The main problem with mechanical harvesting of buckwheat

***Corresponding author:** Beom Seob Lee
Tel: +82-55-586-9454; **Fax:** +82-55-586-9457
E-mail: kmco2000@hanmail.net

is a very large harvesting loss since the long maturing period and easy shattering of seed increase the ratio of black grain. The harvesting loss caused by a combine harvester is classified as header loss, threshing/ separation loss, and non-cutting loss. According to Shiba et al. (1969), the total harvesting loss in Japan ranged from 2.0 to 11.5%, and the threshing/separation loss accounted for as much as 63.2%. Naka et al. (1982) reported that the header loss increased with increase of the maturing period, and the threshing/separation loss drastically increased with increasing supply of crops. Kitakura et al. (2008) showed that as the ratio of black grain decreased, the threshing/separation loss increased, and various types of loss changed depending on the operating conditions of a combine. Iwase and Kumagai (1999) examined how to determine the proper time of harvesting buckwheat by using a combine. Recently, a shatter-resistant variety was developed (Suzuki et al., 2012), and the harvesting loss of shatter-resistant buckwheat when a conventional combine was used was evaluated (Morishita and Suzuki, 2012). The harvesting loss of shatter-resistant buckwheat when a conventional combine was used was evaluated according to the ratio of black grain. In South Korea, a study investigated the effect of the sowing period of buckwheat on growth and yield (2015). However, no study has attempted to develop a combine for harvesting buckwheat, analyze harvesting performance, and examine a new shatter-resistant variety.

Like buckwheat, adlay has a long ripening period, and its shattering drastically increases during this period. In Japan, the mechanized cultivation of adlay was developed for the first time in the early 1980s. The biggest challenges in machine-based harvest were shattering and crop height. The head-feeding combine was available only when the crop height was 130 cm or lower (Tateno, 1984). Short-culmed and shatter-resistant varieties were developed to facilitate mechanized harvesting (Ujihiral and Ishida, 1982 and 1985; Ujihira et al., 1987; Ishida et al., 1997; Nakano et al., 2003; Tetsuka et al., 2010). Takamatsu et al. (1985), Okabe et al. (1987), and Ohtsuka et al. (1985) modified head-feeding combines to make them more suitable for harvesting adlay and analyzed the harvesting characteristics obtained by such modifications. In South Korea, Yi et al. (1997) dealt with yield capacity according to the harvesting period of adlay using a head-feeding combine and reported the ratio of grain loss and the ratios of grain, damaged grain, and foreign materials at the grain outlet. However, only a few studies have attempted to develop a combine for mechanized harvesting, examine harvesting performance, or propose short-culmed and shatter-resistant varieties.

With the intent of developing and commercializing a domestic small 22-kW combine for harvesting miscellaneous cereal crops (Lee and Yoo, 2016 and 2017; Lee et al., 2017), a prototype has been designed and constructed. In this study, we conducted a harvesting test for buckwheat and adlay by using the prototype combine and evaluated its harvesting performance in terms of the harvesting loss, the composition at the grain outlet, and so forth.

Materials and Methods

Prototype small combine

Figure 1 shows the prototype small combine used in the harvesting test for buckwheat and adlay and Table 1 presents the specifications of the primary parts of the prototype combine.

The prototype small combine comprises a diesel engine with the rated power/speed of 22.0 kW/2,600 rpm, three-stage primary and two-stage speed range transmission shifts, a double acting cylinder type threshing part and the working width of 1.2 m. Its structure was similar as those of the compact conventional cutting crop full-feeding combine. It consisted of the following main parts: a diesel engine with the rated power/speed of 22.0 kW/2,600 rpm; a power transmission with selective mesh gears (three-stage primary and two-stage speed range transmission shifts); a header part (including a clutch-type steering system, divider, reel, reciprocating-

Figure 1. Photograph of the prototype small combine for harvesting miscellaneous cereal crops.

Table 1. Specifications of the prototype small combine

Item	Specifications
Engine	Manufacturer/Model: Kukje/ A1100T2-KTR-4 Type: water cooled, 4-stroke, 3 cylinders, diesel Displacement: 1,175 cc, rated power/speed: 15.5/3600 kW/rpm
Transmission	Primary transmission shift: selective gear type high, middle, low 3 stages Speed range transmission shift: selective gear type high, low 2 stages
Crawler	Width x Length: 280 x 920 mm, lug height: 30 mm, no. of link: 38, crawler tread: 775 mm, ground contact pressure: 32.6 kPa
Steering	Steering clutch type
Brake	Wet disk type, mechanical pedal
Hydraulics	Hydraulic pump: gear type, displacement 15 cc/rev., max. pressure 13.7 MPa Header cylinder: inner diameter 70 mm, stroke 240 mm Reel cylinder: inner diameter 50 mm, stroke 90 mm
Reel	Diameter 620 mm, no. of tine 64, pitch of tine 85 mm, width of reel 1.75 mm, reel speed 52 rpm
Cutter	Reciprocating type, width of cutting 1,200 mm, range of cutter height 55-740 mm, no. of cutting blade 15, pitch of cutting blade 76 mm, stroke of cutting blade 76 mm, cutting speed 1.32 m/s
Platform auger	Diameter of auger cylinder 200 mm, height of auger screw 80 mm, auger clearance 15 mm, auger speed 213 rpm
Feeder conveyer	Chain conveyer with angle bar type, width x height x length 430 x 1,418 x 1,250 mm, pitch of angle bar 150 mm, feeding speed 2.0 m/s
Threshing part	#1 threshing cylinder: dia. 425 mm, length 485 mm, 7 mm steel wire teeth, no. of teeth 30, height of teeth 55 mm, cylinder speed 405 rpm, speed of teeth end 11.3 m/s #2 threshing cylinder: dia. 325 mm, length 485 mm, 7 mm steel wire teeth, no. of teeth 20, height of teeth 55 mm, cylinder speed 598 rpm, speed of teeth end 13.6 m/s Concave: steel plate with circular holes, hole size 12Φ Cutting knives: triangle, height x thickness 25 x 3.2 mm, no. of knives 5/row x 10 rows
Separating and cleaning part	Straw walker: width x length 90 x 1,500 mm, opening size 20 x 30 mm Grain pan: tilting angle 5°, no. of opening holes 325, hole dia. 10Φ Grain sieve: : tilting angle 5°, no. of opening holes 725, hole dia. 10Φ Fan: centrifugal type, no. of blade 4, speed 1,540 rpm Oscillating arm: speed 350 rpm, oscillating stroke 30 mm
Tailings rethreshing part	Horizontal conveying auger: outer dia. of screw 120 mm, dia of shaft 20 mm, screw pitch 108 mm, speed 178 rpm Tailings distribution auger: outer dia. of screw 120 mm, dia of shaft 20 mm, screw pitch 108 mm, speed 337 rpm Vertical conveying bucket elevator: vol. of a bucket 230 cm^3, no. of buckets 19, speed 2.4 m/s
Grain conveyer and grain tank	Horizontal conveying: tilting steel plate Vertical conveying bucket elevator: vol. of a bucket 230 cm^3, no. of buckets 30, speed 2.7 m/s Grain tank: capacity 200 L, size of grain outlet 150 x 120 mm

type cutter, platform, and crop supply auger); a crop transferring part (including a chain conveyer with embossed plates attached); a reciprocating cutter and double cylinders threshing part; a separating and cleaning part (including a straw walker, grain pan, straw sieve, grain sieve, and fan); a tailings rethreshing part (including a horizontal conveying auger and a vertical conveying bucket elevator); a grain conveying part (including a vertical conveying tilting steel plate and a vertical conveying bucket elevator for separated and cleaned grain); an operation part (including a grain tank and other components for operating the combine and other parts); a combine frame and cover (Yoon et al., 2017).

Field testing

The harvesting performance of a grain combine is evaluated generally by the grain loss and the quality of grain harvested. The grain loss comprises two parts: the header loss caused by the cutter, reel, platform auger and feeder conveyor; the threshing, separating/cleaning loss caused by the threshing cylinder, concave, straw walker, grain pan, chaffer sieve, grain sieve and air blower. The header loss is comprised of the shattering loss and the gathering loss. The quality of grain harvested is evaluated according to the ratios of components such as the whole grain, the damaged grain, the grain with rachis branch, the immature grain, and MOG in the grain outlet.

The harvesting test for buckwheat was performed on

October 17, 2017 on a buckwheat field located in Garye-myeon, Uiryeong-gun, Gyeongsangnam-do. The harvesting test for adlay was conducted on October 19, 2017 on an adlay field located in Ibanseong-myeon, Jinju-si, Gyeongsangnam-do. The moisture contents of buckwheat were about 19.9% in grain and about 60.8% in stem and leaf. The plant height was approximately 110 cm. Buckwheat cultivated by broadcast sowing was used for the test. The moisture contents of adlay were about 21.4% in grain and about 34.98% in stem and leaf. The plant height was approximately 140 cm. The adlay used in the test was cultivated by planting. The spacing in the row was about 60 cm, and that between plants hill was about 50 cm.

In the preliminary test for buckwheat, where the cutting width of 1.2 m was applied for the prototype, an excessive amount of adlay was provided even with the speed of approximately 0.36 m/s at the low speed (Stage 1) of both the speed range and the primary transmission shifts. This resulted in delaying and clogging in the platform auger, the grain conveying, and the threshing parts. Consequently, operation was not possible. For this reason, the width of cutting work was decreased to about 0.6 to 0.7m, and the test was repeated three times only at the low speed of both the speed range and the primary transmission shifts.

In the preliminary test for adlay, operation was possible in two rows with the speed of 0.45 m/s at the low speed of the speed range transmission shift and the middle speed (Stage 2) of the primary transmission shift. Since adlay had hard stems and grew high, operation was done at various cutting heights to reduce the load on the combine. The maximum height allowing operation was about 90 cm. Accordingly, for adlay, the harvesting test was divided into two parts. One part assessed the cutting height as factor, while the other part assessed the number of working rows and the transmission stage as factors. The part of the test to assess the cutting height was repeated twice with variation of the cutting height from 30 to 60 to 90cm in a single row at the low speed of both the speed range and the primary transmission shifts. The other part of the test to assess the working row and transmission stage was also repeated twice by applying a single row and two rows in sequence and with variation of the transmission stage from the low speed to the middle speed of the primary transmission shift and at the low speed of the speed range transmission shift.

In both harvesting tests for buckwheat and adlay, the following items were calculated: travel speed; grain loss ratios in the header part and the dust outlet; and those of grain, damaged grain, and MOG in the grain outlet (FACT, 2014). The operation distance of each treatment was 20 m. The grain loss ratio in the dust outlet was calculated for the whole operation distance. However, the grain loss ratio in the header part was estimated by sampling for a 1 m distance. The composition of the whole grain, damaged grain, and MOG in the grain outlet was investigated by collecting about 500 g of samples. Duncan's multiple range tests were performed to obtain data of the grain loss ratio and the composition of the grain outlet with a significance level of 5% by using SAS 9.4 software.

Results and Discussion

Buckwheat harvesting

Table 2 presents the grain loss and component ratio of output in the grain outlet, which were obtained by using the prototype combine for harvesting buckwheat. The

Table 2. Grain loss and component ratio of output in grain outlet for harvesting buckwheat

Item		Mean (SD)
Travel speed (m/s)		0.36 (0.01)
Header	Shattering (g/m^2)	34.5 (10.9)
	Ratio of grain loss (%)	8.8 (3.2)
Dust outlet	Separating and cleaning (g/m^2)	51.0 (4.3)
	Ratio of grain loss (%)	12.8 (0.4)
Total grain loss (g/m^2)		85.5 (6.7)
Total ratio of grain loss (%)		21.6 (2.8)
Grain outlet	Ratio of grain (%)	94.1 (0.7)
	Ratio of damaged grain (%)	0.0 (0.0)
	Ratio of material other than grain (%)	5.9 (0.7)

Note 1) Speed range transmission shift: low, primary transmission shift: low, cutting width: 0.6-0.7 m
2) SD: standard deviation

photographs in Figure 2 show the prototype small combine harvesting buckwheat and an output sample in grain outlet.

As shown in Table 2, the total grain loss and the total ratio of grain loss were about 85.5 g/m^2 and 21.6%, respectively for the prototype small combine. The header part loss by shattering accounted for 40.1%, and the dust outlet loss by separating and cleaning accounted for 59.9%.

The total ratio of grain loss depends on climate conditions during cultivation, such as rainfall and wind speed, buckwheat conditions, such as the ratio of black grain, and the operating conditions of the combine. According to Shiba et al. (1969), the total ratio of grain loss usually ranged from 2.0 to 11.5% when a conventional combine was used. Naka et al. (1982) reported that the total ratios of grain loss were 15 to 20% when a head feeding combine was used and 3 to 6% when a conventional combine was used. Kitakura et al. (2008) conducted a test in which buckwheat with the ratio of black grain of 48 to 76% was harvested by a conventional combine with the cutting width of 1.7 to 2.1 m, and buckwheat with the ratio of black grain of 48 to 80% was harvested by a small conventional combine with the cutting width of 1.3 to 1.5 m. The total ratios of grain loss were reported to be 1.1 to 19.8% and 3.2 to 17.9%, respectively. Morishita and Suzuki (2012) used a conventional combine in a harvesting test for buckwheat with the ratio of black grain of 90.95% in 2012. They reported that a conventional variety and a shatter-resistant variety showed total grain loss ratios of 6.7 to 21.2% and 9.6 to 10.1% respectively. In comparison with the result of Kitakura et al. (2008), in which buckwheat had a low ratio of black grain, the total grain loss ratios of this study seemed to be higher. Even in comparison with the results of Kitakura et al. (2008), where buckwheat had a relatively high ratio of black grain, the results of this study were similar or a little higher than those of the conventional variety. They were also higher than the results for the shatter-resistant variety. In particular, in this study, the ratio of grain loss in the dust outlet, which was attributable to shattering as well as separating and cleaning work, turned out to be 12.8%. On the other hand, Kitakura et al. (2008) and Morishita and Suzuki (2012) reported ratios of 1.1 to 8.5% and 1.2 to 4.9%, respectively. Accordingly, it was necessary to improve the separating and cleaning unit. As the header part loss by shattering was due to the shattering characteristics of the buckwheat variety, it is very hard to reduce. It is considered that the overload by high travel speed, the improper sizes of the threshing concave and grain pan hole, slow threshing tooth speed, and high air speed and flow by fan caused the high dust outlet loss by separating and cleaning. In this regard, as for the primary transmission shift of the prototype combine, the selective mesh gear type needed to be changed to hydrostatic transmission (HST) to reduce the travel speed and thus control overload, and make the cutting width of 1.2 m available. The sizes of the threshing concave and grain pan hole needed to be changed from 12 Ø to 15 Ø and from 10 Ø to 8 Ø, respectively. And also

Figure 2. Photographs of the prototype small combine for harvesting buckwheat and output sample in the grain outlet.

speed control to increase threshing tooth speed and decrease the air speed and flow by fan was necessary to improve the separating and cleaning performance for buckwheat harvesting.

When the prototype combine was used to harvest buckwheat, the composition ratio of output of the grain outlet consisted of 94.1% grain, 5.9% MOG, and 0.0% damaged grain as shown in Table 2.

According to Naka et al. (1982), when a head-feeding combine was used for harvest, ratios of MOG and damaged grain accounted for as much as 20% and 3 to 4%, respectively, of the output of the grain outlet. The authors also reported that the use of the conventional combine achieved a ratio of about 80 to 95% of grain in the output of the grain outlet. However, according to Kitakura et al. (2008), when a conventional combine was operated with a cutting width of 1.7 to 2.1 m, the ratios of grain and MOG were 97% or above and 3% or below, respectively. When a small conventional combine with a cutting width of 1.3 to 1.5 m was used, the ratios of grain and foreign materials were 98% or above and 2% or below, respectively. Both results showed higher ratios of grain and lower ratios of MOG than those of the prototype combine used in this study. Therefore, improvement the threshing, separating and cleaning units of the prototype combine was necessary to decrease the ratios of grain loss and MOG in the grain outlet as mentioned in the grain loss.

Adlay harvesting

The photographs in Figure 3 show the prototype small combine harvesting adlay and an output sample in the grain outlet.

Table 3 presents grain loss according to the cutting height of the prototype combine. As seen in Table 3, the stage of the primary transmission was fixed to the low speed, and the cutting width was set to a single row. When the cutting heights of 30, 60, and 90 cm were applied, the total amounts of grain loss were about 161.0, 137.6, and 142.0 g/m^2, respectively and the total ratios of grain loss were 42.8, 36.8, and 36.3%, respectively. The total ratio of grain loss was larger at the cutting height of 30 cm than at those at 60 and 90 cm. There was no difference between the cutting heights of 60 and 90 cm with respect to the total ratio of grain loss. The ratio of grain loss due to shattering in the header was 6.9 to 9.8%, that related to gathering heads of grain, which were cut and had fallen in the header, were 22.7 to 33.6%, and that of the dust outlet due to the threshing, separating, and cleaning was 2.3 to 4.7%. The gathering loss accounted for a large portion. The ratio of grain loss in the header was higher at the cutting height of 30 cm than those at 60 and 90 cm. There was no difference between the cutting heights of 60 and 90 cm with respect to the ratio of grain loss. The ratio of grain loss in the dust outlet did not change according to the cutting height.

Table 4 presents the grain loss according to the number of harvesting rows and the stage of the primary transmission shift. As seen in the table, when the cutting

Figure 3. Photographs of the prototype small combine for harvesting adlay and output sample in the grain outlet.

Table 3. Grain loss by the cutting height for harvesting adlay

Item		Cutting height					
		30 cm		60 cm		90 cm	
Travel speed (m/s)		0.35 (0.01)		0.34 (0.01)		0.35 (0.01)	
Header	Shattering (g/m²)	26.3 (10.7)		29.6 (0.4)		38.0 (11.1)	
	Gathering (g/m²)	126.3 (13.6)		90.9 (19.0)		88.4 (23.2)	
	Subtotal (g/m²)	152.5 (2.8)		120.5 (19.3)		126.4 (34.3)	
	Ratio of grain loss (%)	40.5 (1.9)	a	32.1 (3.3)	b	32.5 (0.5)	b
Dust outlet	Separating and cleaning (g/m²)	8.5 (2.2)		17.1 (6.2)		15.1 (10.1)	
	Ratio of grain loss (%)	2.3 (0.5)	a	4.7 (1.9)	a	3.8 (1.7)	a
Total grain loss (g/m²)		161.0 (0.6)		137.6 (13.1)		142.0 (44.6)	
Total ratio of grain loss (%)		42.8 (1.4)	a	36.8 (1.5)	b	36.3 (2.2)	b

Note 1) A row harvesting, speed range transmission shift: low, primary transmission shift: low
2) Gathering loss: the cutting heads of grain fallen on the ground
3) Value in parenthesis means standard deviation.
4) a, b: Different letters in a row are significantly different ($p<0.05$).

Table 4. Grain loss by the number of harvesting row and the stage of primary transmission shift for harvesting adlay

Item		Number of harvesting row							
		1				2			
		Stage of primary transmission shift							
		1(low)		2(middle)		1(low)		2(middle)	
Travel speed (m/s)		0.34(0.01)		0.46(0.01)		0.32(0.01)		0.45(0.01)	
Header	Shattering (g/m²)	29.6 (0.4)	a	26.7 (1.4)	ab	20.4(4.7)	b	10.2(1.7)	c
	Gathering (g/m²)	90.9(19.0)	a	96.5(8.9)	a	102.4(12.8)	a	72.7(2.7)	a
	Subtotal (g/m²)	120.5(19.3)		123.9(6.4)		122.8(8.1)		82.9(4.4)	
	Ratio of grain loss (%)	32.1(3.3)	a	32.0(0.6)	a	30.3(0.9)	a	27.6(0.6)	a
Dust outlet	Separating and cleaning (g/m²)	17.1(6.2)		21.9(0.2)		15.8(7.1)		24.4(1.3)	
	Ratio of grain loss (%)	4.7(1.9)	b	5.7(0.1)	ab	4.9(0.9)	b	8.2(0.8)	a
Total grain loss (g/m²)		137.6(13.1)		145.8(6.6)		138.6(11.7)		107.3(3.1)	
Total ratio of grain loss (%)		36.8(1.5)	a	37.7(0.7)	a	35.2(1.8)	a	35.8(0.2)	a

Note 1) Speed range transmission shift: low, cutting height: 60 cm
2) Gathering loss: the cutting heads of grain fallen on the ground
3) Value in parenthesis means standard deviation.
4) a, b: Different letters in a row are significantly different ($p<0.05$).

height was fixed to 60 cm, the total amounts of grain loss and the total ratios of grain loss were 137.6 g/m^2 and 36.8%, respectively, in a single row and at the low speed of the primary transmission shift, 145.8 g/m^2 and 37.7% in a single row and at the middle speed of the primary transmission shift, 138.6 g/m^2 and 35.2% in two rows and at the low speed of the primary transmission shift, and finally 107.3 g/m^2 and 35.8% in two rows and at the middle speed of the primary transmission shift. The ratio of grain loss due to shattering in the header was 3.4 to 7.9%, that related to gathering heads of grain, which were cut and had fallen in the header, were 24.2 to 25.2%, and that of the dust outlet due to threshing, separating, and cleaning was 4.7 to 8.2%. The gathering loss accounted for a large portion. The ratio of grain loss due to shattering in the header was lower in the single row harvest than the double row harvest and at the middle speed than the low speed of the primary transmission shift. However, there was no significant difference in the gathering loss according to the number of harvesting rows or the stage of the primary transmission shift. Since the gathering loss accounted for a large portion of the ratio of grain loss in the header, neither the number of harvesting rows nor the stage of the primary transmission

Table 5. Component ratio of output in grain outlet by the cutting height for harvesting adlay

Item	Cutting height					
	30 cm		60 cm		90 cm	
Travel speed (m/s)	0.35 (0.01)		0.34 (0.01)		0.35 (0.01)	
Ratio of whole grain (%)	94.3 (0.9)	a	91.4 (3.3)	a	93.5 (2.1)	a
Ratio of grain with rachis branch (%)	0.6 (0.1)	b	1.2 (0.3)	a	0.9 (0.1)	ab
Ratio of immature grain (%)	0.7 (0.4)	b	1.9 (0.1)	a	0.8 (0.2)	b
Ratio of damaged grain (%)	0.0 (0.0)	a	0.0 (0.0)	a	0.0 (0.0)	a
Total ratio of grain (%)	95.6 (1.1)	a	94.5 (3.1)	a	95.3 (1.8)	a
Ratio of material other than grain (%)	4.4 (1.1)	a	5.5 (3.1)	a	4.7 (1.8)	a

Note 1) A row harvesting, speed range transmission shift: low, primary transmission shift: low
2) Value in parenthesis means standard deviation.
4) a, b: Different letters in a row are significantly different ($p<0.05$).

Table 6. Component ratio of output in grain outlet by the number of harvesting row and stage of primary transmission shift for harvesting adlay

Item	Number of harvesting row							
	1				2			
	Stage of primary transmission shift							
	1(low)		2(middle)		1(low)		2(middle)	
Travel speed (m/s)	0.34 (0.01)		0.46 (0.01)		0.32 (0.01)		0.45 (0.01)	
Ratio of whole grain (%)	91.4 (3.3)	a	91.6 (1.1)	a	93.5 (0.7)	a	90.7 (0.1)	a
Ratio of grain with rachis branch (%)	1.2 (0.3)	a	0.9 (0.3)	a	0.9 (0.1)	a	0.8 (0.2)	a
Ratio of immature grain (%)	1.9 (0.1)	a	1.9 (0.0)	a	1.4 (0.2)	b	1.7 (0.1)	ab
Ratio of damaged grain (%)	0.0 (0.0)	a	0.0 (0.0)	a	0.0 (0.0)	a	0.0 (0.0)	a
Total ratio of grain (%)	94.5 (3.1)	a	94.3 (1.0)	a	95.8 (0.9)	a	93.1 (0.3)	a
Ratio of material other than grain (%)	5.5 (3.1)	a	5.7 (1.0)	a	4.2 (0.9)	a	6.9 (0.3)	a

Note 1) Speed range transmission shift: low, cutting height: 60 cm
2) Value in parenthesis means standard deviation.
3) a, b: Different letters in a row are significantly different ($p<0.05$).

shift generated any significant difference. The ratio of grain loss in the dust outlet was higher in the double row harvest than in the single row harvest and at the middle speed than at the low speed of the primary transmission shift. This indicates that the ratio of grain loss in the dust outlet was proportional to the adlay input into the combine.

The ratio of grain loss during the harvest of adlay depends heavily on variety characteristics, such as crop height and shattering property; crop conditions, such as moisture contents of stem and grain and the ratio of matured grain; and the operating conditions of the combine, such as travel speed and cutting height. Yi et al. (1997) conducted an adlay harvesting test using a head-feeding combine and compared the result with that of manual harvesting. The ratio of grain loss by the combine ranged from 1.4 to 6.6%. Fujioka et al. (1986) reported that the shattering rates were 7.1% by manual harvesting and 8.8 to 16.6% by combines. Takamatsu et al. (1985) performed a harvesting test for adlay by using a head-feeding combine. It turned out that the total ratio of grain loss was 13.5 to 33.2% at the travel speed of about 0.2 m/s and the cutting height of 6.6 to 35.8 cm, and the grain loss ratio in the header ranged from 2.3 to 30.4%. Ohtsuka et al. (1985) modified a head-feeding combine to assess the harvesting performance. Before the combine was modified, the travel speed was about 0.2 m/s or below, the working width was 0.6 m, and the cutting height was 30 to 49 cm. Under these conditions, the total ratio of grain loss was 3.6 to 18.5%, and the grain loss ratio in the header was 0.2 to 12.8%. On the other hand, when the combine was modified, the travel speed could increase up to about 0.3 to 0.4 m/s, and the working width was also extended to 0.9 m. Accordingly, the total ratio of grain loss was 3.7 to 19.6%, and the grain loss ratio in the header was 1.9 to 6.2%. The authors also reported that when the conventional combine was used, the total ratio of grain loss was 7.3 to 12.8% and the grain loss ratio in the header was 0.7 to 2.4%. Okabe et al. (1987) also modified a head-feeding combine for harvesting adlay. Their harvesting test showed that the total ratio of grain loss was about 28.5% at the crop height of 2 m, but it decreased to 5.7 to 13.0% at the crop height of 1.4 m or lower. In this study, when the proposed prototype combine was used, the gathering loss of 22.7 to 33.6% accounted for the largest portion of the total ratio of grain loss. Gathering loss occurs when heads of grain, which are cut, are caught by the tine attached to a reel bar and fall on the ground. This type of loss hardly occurs during the harvesting operation of a combine. Accordingly, as improvements in the structure and operation of the reel, the reel position from the cutter, the setting angle of the reel tine could almost completely eliminated gathering loss, the total ratio of grain loss is expected to be lowered to about 10.0 to 12.6%. Among the combine harvesting test results of Yi et al. (1997), Takamatsu et al. (1985), Ohtsuka et al. (1985), and Okabe et al. (1987), some of the total ratios of grain loss were lower than that of this study using the prototype combine. This may be attributed to the different conditions of adlay and combine operation. In other words, adlay was harvested earlier in the above studies, so the moisture content was higher, and the ratios of damaged or immature grain were high, or the combine travel speed was slower. Thus, if the gathering loss of the prototype combine is reduced by improvements and a new variety is developed that has a low crop height and high shattering resistance for combine harvesting, the total ratio of grain loss will become similar to or lower than those of the combines used in the above studies.

Table 5 presents the component ratio of output in the grain outlet according to the cutting height for harvesting adlay. As seen in the table, the ratio of whole grain was 94.5 to 95.6%, and the ratio of material other than grain was 4.4 to 5.5%. Both ratios showed no significant difference in relation to the cutting height. Among the grains in the grain outlet, the ratio of whole grain was 91.4 to 94.3%, that of grain with rachis branch was 0.6 to 1.2%, that of immature grain was 0.7 to 1.9%, and that of damaged grain was 0.0%.

Table 6 presents the component ratio of output in the grain outlet according to the number of harvesting rows and the stage of the primary transmission shift for harvesting adlay. As seen in the table, the ratio of grain was 93.1 to 95.8%, and that of MOG was 4.2 to 6.9%. Both the number of harvesting rows and the stage of the primary transmission shift had no significant influence on the ratios. Among the grains in the grain outlet, the ratio of whole grain was 90.7 to 93.5%, that of grain with rachis branch was 0.8 to 1.2%, that of immature grain was 1.4 to 1.9%, and that of damaged grain was 0.0%.

Yi et al. (1997) conducted a harvesting test using a head-feeding combine. They reported that the ratios of ripened grain, immature grain, and MOG were 54.9 to 80.7%, 22.1 to 6.1%, and 23.1 to 13.2%, respectively, 40 to 60 days after flowering. It also turned out that the ratio of ripened grain increased, but those of immature grain and MOG decreased. The harvesting test of Takamatsu et al. (1985) using a head-feeding combine showed that the ratios of whole grain, damaged grain, broken grain, grain with rachis branch, and MOG in the grain outlet were 70.1 to 80.5%, 7.4 to 11.0%, 3.2 to 21.1%, 0.9 to 2.1%, and 0.5 to 3.2%, respectively. According to Ohtsuka et al. (1985), before a head-feeding combine was modified, the ratios of whole grain, damaged grain, immature grain, and MOG in the grain outlet were 73.0 to 85.5%, 5.9 to 21.1%, 3.7 to 4.0%, and 1.9 to 4.9%, respectively. After the combine was modified, the ratios of whole grain, damaged grain, grain with rachis branch, and MOG in the grain outlet were 73.8 to 95.6%, 2.0 to 25.7%, 0.0 to 1.1%, and 0.1 to 2.8%, respectively. When a conventional combine was used, the ratios of whole grain, damaged grain, grain with rachis branch, and MOG in the grain outlet were reported to be 77.3 to 78.9%, 15.9 to 16.9%, 0.4 to 0.9%, and 4.8 to 4.9%, respectively. In comparison with the results of the above studies, the prototype combine assessed in this study showed better performance in terms of the ratios of whole grain and damaged grain in the output of the grain outlet and similar performance in terms of the ratio of grain with rachis branch but inferior performance in terms of the ratio of MOG. Consequently, as for the primary transmission shift of the prototype combine, the selective mesh gear type needed to be changed to hydrostatic transmission (HST) to control the harvesting speed comfortably. To decrease the ratio of MOG, the sizes of the threshing concave and grain pan hole needed to be changed from 12 Ø to 15 Ø and from 10 Ø to 12 Ø, respectively.

Conclusions

A prototype small combine with the rated power/speed of 22.0 kW/2,600 rpm, three-stage primary and two-stage speed range transmission shifts, a double acting cylinder type threshing part and the working width of 1.2 m for harvesting miscellaneous cereal crops was designed and constructed, and its harvesting performance was evaluated for buckwheat and adlay. In case of buckwheat harvest, the total ratio of grain loss was about 21.6%. The grain and MOG ratios at the grain outlet were 94.1% and 5.9% respectively. In the case of adlay harvest, when the cutting height was 60 cm, the total ratio of grain loss ranged from 35.2 to 37.7%. The grain and the MOG ratios at the grain outlet ranged from 93.1 to 95.8% and from 4.2 to 6.9%, respectively. Field testing demonstrated that the prototype small combine could efficiently harvest buckwheat and adlay. However, to improve the harvesting performance, that is, to decrease the ratios of grain loss and MOG in the grain outlet, components including the transmission, the reel, and the separating and cleaning unit need to be improved. In addition, a suitable variety for mechanized harvesting should be developed. With such improvements, the prototype small combine could be effectively used to mechanize the harvesting of buckwheat and adlay on small family farms or in semi-mountainous areas.

Conflict of Interest

The authors have no conflicting financial or other interests.

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