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Development of Single-tractor Integrated Multi-purpose Forage Harvester

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Abstract

Purpose: To improve the insufficient mechanized forage harvesting system, an integrated forage harvester that produces midsize round bales was developed. **Methods:** The harvesting performance of the developed harvester was tested in a forage plantation. The harvesting performance was evaluated by investigating the bale production performance and residue ratios of the harvester at three levels of tractor driving speeds. **Results:** The bales outputs per hour by driving speed shown by the harvester were 30 bales (6.8 MT) at 2.3 km/h, 36 bales (8.4 MT) at 3.2 km/h, and 44 bales (10.5 MT) at 5.1 km/h in the case of rye-straw. In the case of rice-straw, they were 43 bales (8.8 MT) at 4.3 km/h, 44 bales (9.7 MT) at 5.0 km/h, and 48 bales (10.7 MT) at 6.2 km/h. In the case of Italian ryegrass (IRG), they were 35 bales (10.7 MT) at 7.0 km/h, 37 bales (12.0 MT) at 8.3 km/h, and 38 bales (13.2 MT) at 9.5 km/h. The average ratios of residues to the available quantities were 2.61% in the case of rye-straw, 1.89% in the case of rice-straw, and 1.57% in the case of IRG. When residues smaller than 200 mm, which cannot be collected, were excluded, the residue ratios of all crops were good, as they did not exceed 1.0%. **Conclusions:** Since the baling and wrapping functions, which had been separately operated, were integrated into the developed harvester, the developed harvester is expected to maximize bale production efficiency and increase labor productivity, thereby increasing farming profitability.

Keywords: Bale, Forage, Integrated multi-purpose forage harvester, Performance test

Introduction

Forage, which is used as feed for ruminants, has been grown in 258,675 ha of farmlands in South Korea, and the current self-sufficiency rate is approximately 82%. The forage produced in South Korea consists of Italian ryegrass (IRG) 53.1%, rye-straw 14.7%, blue-barley 6.4%, sorghum 6.3%, maize 4.4%, oat 1.0%, rape 0.2%, and other crops 14%, and the total output was 2,413,000 tons in 2013 (MAFRA, 2014). The power requirement for forage harvesting has been reduced by 94.3% through mechanized bale production using harvesters at 59 h/ha compared to manpower harvesting at 880 h/ha (MAFRA, 2011).

Forage harvesters that have led stockbreeding revolutions throughout the world have mainly been developed in North America and Europe. Hay balers (Ummo Luebbens, 1910) were developed first; subsequently, fixed-chamber (Vermeer, 1972) and variable-chamber (Wilhelm Kemper, 1973) hay balers were studied and developed (Skromme, 1985). Forage harvesters have been continuously studied and developed even in the 2000s. Kim and Kim (2000) developed a tying-unit controller for variable-chamber round baler. Yoo et al. (2007) developed a self-propelled round baler. Kawaide et al. (2013) developed a variable-chamber round baler installed with a chopper. To reduce the inefficient energy consumption that occurs in forage harvesters, the power requirement and energy consumption of baler operation were analyzed (Kim et al. 2011; Freeland and Bledsoe, 1988). Shito and Yamana (2002) studied methods of reducing the labor power required during maize harvesting and ensiling.

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Most forage harvests are inefficient because a combine harvester produces bales and a separate wrapper performs vinyl wrapping. Despite the existence and use of integrated harvester-wrappers, which are harvesters attached with a wrapper at the end, there are challenges when used on narrow rural roads and on small arable land because they require wide turning spaces owing to their sizes. In this study, an integrated forage harvester that produces midsize round bales was developed for attachment to 90PS tractors commonly used by stockbreeding farmhouses. During development and fabrication, bale harvesting and vinyl wrapping were integrated so that they could be performed on one tractor. The integration of the harvesting and vinyl wrapping functions, which are usually performed separately, into one unit maximizes bale production efficiency and improves labor productivity, which will increase farming profitability.

Materials and Methods

Integrated multi-purpose forage harvester design and development

The forage harvester developed in this study was designed and fabricated so that both bale rolling and wrapping could be done successively in the rolling chamber. It was also designed to be attached to the 3-point hitch of a tractor for convenient operation. The forage harvester consists of five major devices (Figure 1): a power take-off (PTO) connecting device, a pick-up device, a rotor device, a vinyl wrapping device, a roller device and an erecting device that is separately attached. It was also designed so that the angle of its main body could be adjusted according to harvesting environments (e.g., sloped terrain) using the hydraulic pressure of the tractor.

The working process of the harvester is as follows. (1) The harvester is mechanically connected to the tractor through the PTO connecting device. (2) The pick-up device collects forage from the forward area below the harvester. (3) The rotor device cuts the forage supplied by the pick-up device. (4) The roller device rolls the forage supplied by the rotor device to form bales. (5) The vinyl wrapping device wraps the formed bales with vinyl to finally produce wrapped bales. The developed forage harvester had a target specification to produce midsize bales having diameters of 100 cm and lengths of 100 cm.

Rotor device

The rotor device cuts the forage collected by the pick-up device at the front bottom of the harvester and supplies it to the roller device inside the harvester. The device (Figure 2) basically consists of a bottom frame [(3)-(a)], main frame [(3)-(d), (3)-(b)], knife frame [(3)-(e)], and shaft [(3)-(c)] (material: SCM440). The knives [(3)-(b)], the fixing knife [(3)-(g)], and the scraper [(3)-(f)] cut the forage and supply the cut forage to the roller device using their turning force. The structure of the rotor device was analyzed using the finite element method (Autodesk simulation mechanical 2015, Autodesk). The verification results were as follows: at 14 bars, the maximum displacement was 1.8 mm [(1)], the maximum stress was 172.39 MPa [(2)], and a safety factor of 3.97 satisfied the minimum safety factor of 2.6 for the maximum load (Figure 2).

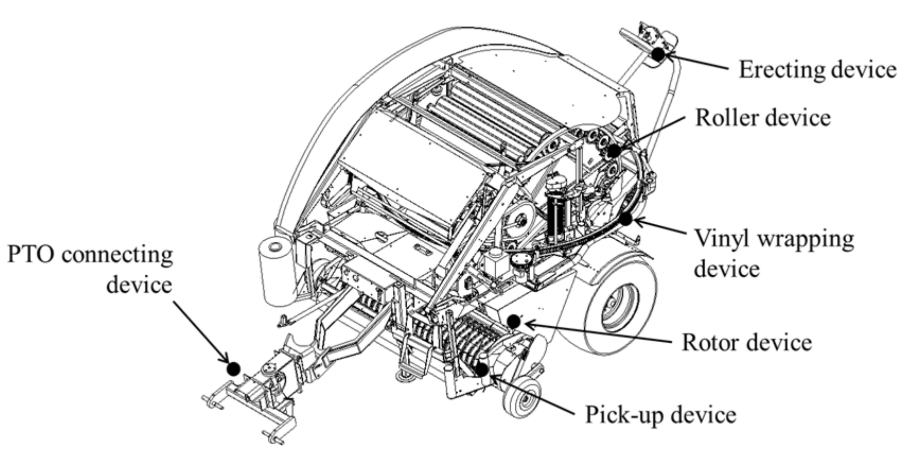
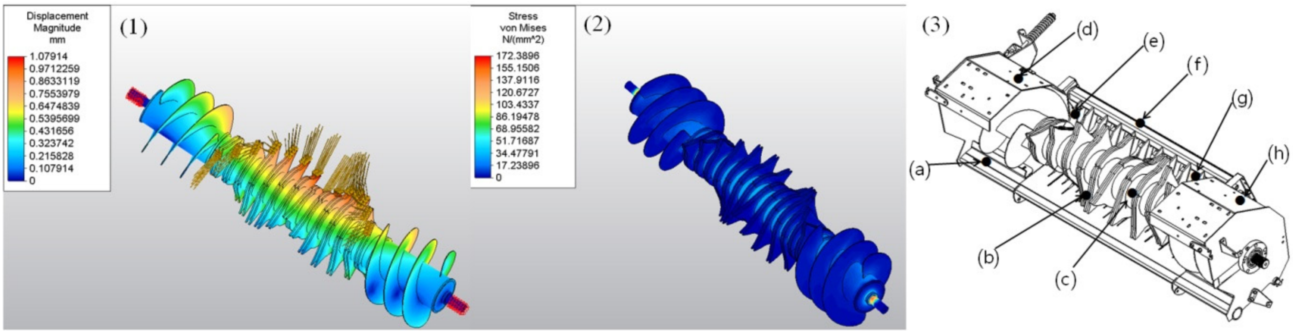
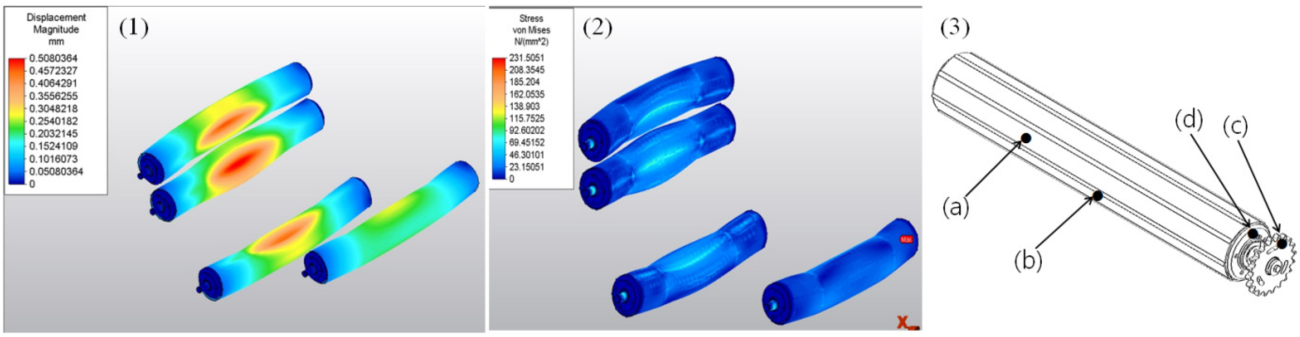


Figure 1. Schematic of the developed integrated multi-purpose forage harvester.



(1) Structural analysis for displacement; (2) Structural analysis for stress; (3) Schematic of rotor device [(a) Bottom frame; (b) Knives; (c) Shaft; (d) Main frame left; (e) Knife frame; (f) Scraper; (g) Fixing knife; (h) Main frame right]

Figure 2. Structural analysis and schematic of rotor device.



(1) Structural analysis for displacement; (2) Structural analysis for stress; (3) Schematic of roller device [(a) Drum; (b) Rectangular protrusion; (c) Driving gear; (d) Shaft]

Figure 3. Structural analysis and schematic of roller device.

Roller device

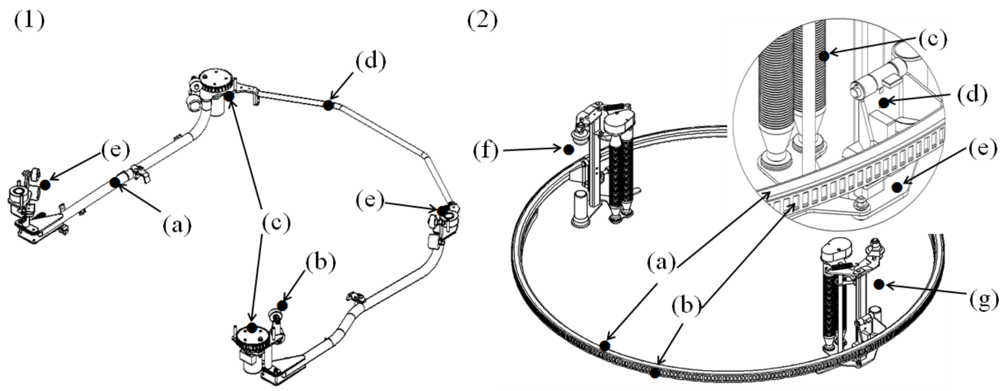
The roller device forms the forage supplied by the rotor device into bales. This device has 18 rollers arranged in a circle, and each roller helps form round bales with high rotating pressure. The roller devices included one roller for material supply, twelve rollers for bale formation, two rollers for power transmission, and three rollers for top rotation (Figure 3). Each roller consists of a drum [(3)-(a)] with rectangular protrusions [(3)-(b)], driving gear [(3)-(c)], and shaft [(3)-(d)] (material: SS400) to transmit the rotating force. The structure of the designed roller device was analyzed using the finite element method (Autodesk simulation mechanical 2015, Autodesk). The verification results were as follows: when the contact area of the harvester was 1,200 mm^2 and 600 N of force was applied to each rectangular protrusion [(3)-(b)] at a pressure of 10 bar, the maximum displacement was 0.51 mm [(1)], the maximum stress was 93.7 MPa [(2)], and the safety factor of 2.6 satisfied the minimum safety factor for the maximum load (Figure 3).

Vinyl wrapping device

The vinyl wrapping device wraps the bales that have been formed by the roller device with vinyl. This device consists of a driving part [(1)] and a passive part [(2)] (Figure 4). The driving part includes driving gears [(1)-(c)] and guide rollers [(1)-(b), (1)-(e)] that rotate the passive part. The passive part includes a passive ring [(2)-(a)] with passive gears [(2)-(b)] and two wrap holders [(2)-(f), (2)-(g)] that rotate to perform the vinyl wrapping function. The vinyl wrapping device was designed so that the passive ring would rotate at a high speed of 28 rpm while the guide rollers would rotate at 25 rpm around the two wrap holders installed with vinyl rolls.

Proximity sensor for forage harvester

The forage harvester is controlled with seven equivalent proximity sensors. The positions where the sensors are installed and the functions of the sensors are as follows. A top hat angle sensor checks whether the top cover is open or closed. A net knife out sensor checks whether the knife blade for cutting nets has been installed at its normal



(1) Vinyl wrapper driving part [(a) Support structure; (b) Guide roller A; (c) Driving gear; (d) Adjustment structure; (e) Guide roller B]; (2) Vinyl wrapper passive part [(a) Passive ring; (b) Passive ring gear; (c) Wrap guide; (d) Wrap mounted plate; (e) Wrap holder mounted plate; (f) Wrap holder left; (g) Wrap holder right]

Figure 4. Schematic of vinyl wrapping device.

position. A bale success sensor checks for the completion of the bales being produced. A ring pulse sensor controls the forward/reverse directions and revolution counts of the passive ring. A cutter down sensor checks the home position of the vinyl cutting knife blade after completion of wrapping. A ring zero sensor checks the home position of the passive ring. A rotor knife sensor checks the home position of the rotor knife.

Forage harvesting experiment

Test environment

Forage harvesting experiments were conducted in major feed crop plantations to evaluate the field performance of the developed harvester. The information on the experimental environment is as follows, and the soil properties and components were analyzed by the Foundation of Agricultural Technology Commercialization and Transfer (FACT) (Table 1).

The experimental fields were plantations of rye-straw (sown in autumn), rice-straw (sown in spring), and IRG (sown in spring), whose soil properties were sandy loam, loam, and clay loam, respectively, with pH values of 6.5, 6.8, and 6.9, respectively, EC values of 0.55, 0.48, and 0.59 d/Sm, respectively, and organic matter values of 113, 24, and 31 g/kg, respectively. In addition, the experimental fields had the characteristics of upland, paddy field, and paddy field (forage only), respectively, all for double cropping, the gradients were 2%-7%, 0%-2%, and 0%-2%, respectively, and the drainage classes were excellent, very excellent, and very excellent, respectively.

Forage environment

The feed crops used in the performance test were three

Table 1. Soil environment of experimental area

Forage crop		Rye-straw	Rice-straw	IRG
Area	Districts	Hoengseong-gun	Ansung-si	Pyeongtack-si
	Latitude	37°31' 34.14"N	36°59' 10.11"N	36°59' 44.71"N
	Longitude	127°50' 48.65"N	127°10' 46.15"N	127°0' 10.72"E
Soil*	Characteristics	Sandy Loam	Loam	Clay Loam
	pH	6.5	6.8	6.9
	EC (d/Sm)	0.55	0.48	0.59
	Organic matter (g/kg)	113	24	31
Topography**	Land-use	Upland	Paddy filed	Paddy filed
	Gradient (%)	2–7	0–2	0–2
	Drainage class	Excellent	Very excellent	Very excellent

* Analysis test report (FACT, 16-Soil-1-01188/16-Soil-1-01262/16-Soil-1-01256, 2016)
** Korean Soil Information System (RDA, http://soil.rda.go.kr, 2016)

Table 2. Forage environment of experimental area

Forage crop	Rye-straw*	Rice-straw*	IRG*
Moisture content (%)	70.99	15.80	25.06
Crude protein (%)	1.71	2.88	10.52
Crude fat (%)	1.11	3.33	3.54
Crude fiber (%)	13.94	28.79	24.45
Crude ash (%)	1.28	7.70	11.11
NDF (%)	22.34	56.31	44.29
ADF (%)	14.15	32.10	25.21

*Analysis test report (FACT, 16-C-1202/16-C-1510/16-C-1356, 2016)

species: IRG, rice-straw, and rye-straw. IRG and rye-straw are representative feed crops in South Korea with feed crop cultivation area composition fractions of 53.1% and 14.7% respectively (RDA, 2015). Rice-straw is a by-product of rice, which is a feed crop, and its output per year throughout the country is 4.81 million tons in 797,957 ha of fields (Statistics Korea, 2015). Samples not enhanced with any additive were collected from the experimental fields. The forage contents are listed in Table 2. The moisture contents of the rye-straw, rice-straw, and IRG samples were 70.99%, 15.80%, and 25.06%, respectively, their crude protein contents were 1.71%, 2.88%, and 10.52%, respectively, their crude fat contents were 1.11%, 3.33%, and 3.54%, respectively, their crude fiber contents were 13.94%, 28.79%, and 24.45%, respectively, and their crude ash contents were 1.28%, 7.70%, and 11.11%, respectively. In addition, their contents of non-detergent fiber (NDF), which is an indicator of palatability to ruminants, were 22.34%, 56.31%, and 44.29%, and their contents of acid detergent fiber (ADF), which is a dry matter digestibility indicator, were 14.15%, 32.10%, and 25.21%, respectively.

Tractor and harvester used for experiment

The specifications of the tractor and harvester used in the performance test are given in Table 3. In order to regulate certain bale production tare (40 bales/h) by the different forage collecting (i.e., mowing) density, two 90 hp-range (67 kW) tractors having different drive speed were used in the experiment. The specifications of the D851 tractor (Daedong, Daegu, Korea) used in the experiment to harvest rye-straw are as follows: maximum PTO output of 83 ps (61 kW) at an engine rev count of 2,000 rpm and driving speeds in a range of L3 (0.81 km/h) to H3 (17.92 km/h) at traction power in a range from 1,048 kgf (10.28 kN) to 2,726 kgf (26.73 kN). The specifications of the TTV610 tractor (Deutz-Fahr, Bavarian, Germany) used in the experiment to harvest rice-straw and IRG are as follows: maximum PTO output of 102 ps (75 kW) at an engine rev count of 2,100 rpm and a driving speed of 0 km/h to 34.0 km/h. The developed harvester produces midsize round bales with diameters of 1,000 mm and lengths of 1,000 mm.

Field experiment method

The field experiments were conducted while the outputs of an individual tractor were fixed at a rated engine rev count of 2000 rpm and a PTO rev count of 540 rpm. To measure the field work capacity, the bale output per hour was measured in a state where hay-raking had been completed in advance with a disc-mower and a hay-rake

Table 3. Specifications of the tractor and integrated multi-purpose forage harvester

Tractor				Forage harvester***		
Model		D851*	TTV610**	Model		Multi-pro
PTO power/speed (ps/rpm)		83/2,000	102/2,100	Applicable tractor (ps)		≥90–99
Weight (kg)		3,840	7,410	Weight (kg)		2,200
Dimensions	Width (mm)	2,010	2,520	Bale	Diameter (mm)	1,000
	Length (mm)	4,075	5,230		Length (mm)	1,000
	Height (mm)	2,735	2,960	Dimensions	Pick-up (mm)	1,800
Wheel distance (mm)		2,142	2,767		Width (mm)	2,376
Min. Rotation radius (mm)		3,440	5,120****		Length (mm)	2,880
Standard PTO speed (rpm)		540	540		Height (mm)	2,076

* Test report 04-M-1-37 (NAMRI/RDA, 2004)
** Test report 12-M-6-75 (FACT, 2012)
*** Specifications of the developed harvester, 2016
**** Specifications of the manufactory Ltd., (Deutz Fahr, 2016)

machine. The residue ratio was determined as the ratio of forage residues after using the harvester to the available quantity of forage before using the harvester. The available quantity of forage was obtained by measuring the weight of forage per meter in the experiments for each crop, obtaining the average value, and multiplying the average value by the working distances to make one bale by driving speed. The residues were obtained in the same manner. In this case, the quantities of residues with lengths exceeding 500 mm and those with lengths in a range of 200 mm to 500 mm were measured separately, and the quantities of residues with lengths shorter than 200 mm, which could not be collected, were obtained from the difference between the quantities of residues obtained and the available quantity of forage. In addition, to evaluate the work performances by the device of the harvester, the working time was divided into netting time, wrapping time, discharging time, and other time; throughout operation, the times were measured three times, and the average values were obtained. The diameter, length, and weight of the bales produced were measured three times in each experiment and the average values were obtained. In addition, for the measurement of the available quantities and residues, the forage that could not be harvested because it was below the tractor tires during the hay-raking using the disc-mower and hay-rake machine was classified into extraneous weight.

Results and Discussion

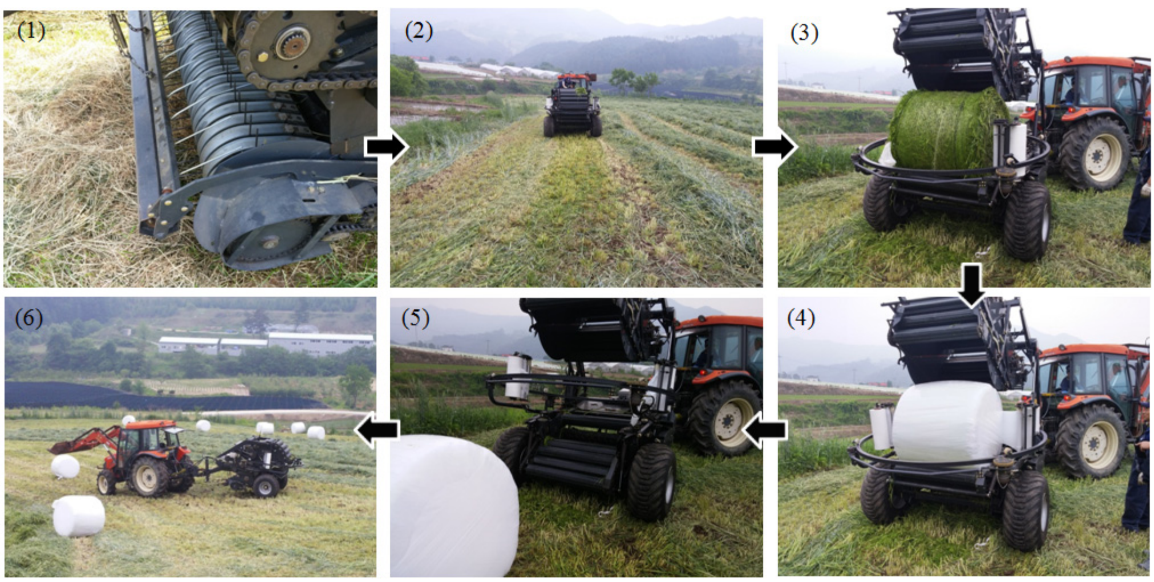
Forage collecting conditions

Before the harvester experiments, the average distribution densities of forage for each crop before and after raking were obtained based on the working widths and the collected widths before and after using the disc-mower and hay-rakes machine. The raked quantity of rye-straw was 2.30 kg-forage/m^2 before mowing using a disc-mower, which increased by 141% to 3.25 kg-forage/m^2 after mowing. The raked quantity of rice-straw increased by 614% from 0.567 kg-forage/m^2 before mowing to 3.48 kg-forage/m^2 after mowing, and that of IRG increased by 157% from 1.53 kg-forage/m^2 before mowing to 2.40 kg-forage/m^2 after mowing.

Performance test of tractor for harvesting forage

Operating efficiency of the integrated multi-purpose forage harvester

The bale production capacity of the harvester was tested on the crops at three levels of tractor driving speeds. The three levels of tractor driving speeds were determined within a range that enabled bale production of 30 to 45 bales per hour considering the available quantities of forage. The working time was divided into pick-up, rolling, netting, wrapping, discharging, preparation, and other times for separate measurements (Figure 5).



(1) Pick-up; (2) Rolling; (3) Netting; (4) Wrapping; (5) Discharging; (6) Preparations

Figure 5. Performance test for tractor with an attachable integrated multi-purpose forage harvester.

Table 4. Bale production capacity in accordance with the changes in the driving speed

Forage crop		Rye-straw			Rice-straw			IRG		
Driving speed (km/h)*		2.3	3.2	5.1	4.3	5.0	6.2	7.0	8.3	9.5
Working time (s/bale)	Pick-up·Rolling*	71.3	51.2	32.3	36.5	33.7	28.0	58.2	52.4	48.5
	Netting*	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
	Wrapping*	30.4	30.4	30.4	30.4	30.4	30.4	30.4	30.4	30.4
	Discharging*	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
	etc.*	8.0	8.0	8.0	6.5	6.5	6.5	5.0	5.0	5.0
	Total**	120.4	100.3	81.4	84.1	81.3	75.6	104.3	98.5	94.6
Working distance (m/bale)*		45.0	45.2	46.2	43.5	46.8	47.9	113.7	120.6	128.2
Bale specifica-tions*	Diameter (mm)	1,023	1,048	1,052	1,025	1,053	1,058	1,030	1,050	1,060
	Length (mm)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
	Weight (kg)	232.5	233.5	238.0	204.5	220.0	225.0	309.0	327.5	347.5

* This category represents average value of samples at each process
** The total working time is obtained by adding the average value for each process

The working time was closely related to the driving speeds and working speeds (Table 4). The ratios of pick-up and rolling time to working time according to three levels of driving speeds decreased as the level became higher from 59.2% to 51.0% to 39.7% in the case of rye-straw; these ratios decreased from 43.4% to 41.5% to 37.0% in the case of rice-straw; these ratios decreased from 55.0% to 52.4% to 50.6% in the case of IRG. The average ratios were 50.0% in the case of rye-straw, 40.6% in the case of rice-straw, and 52.7% in the case of IRG. The working times of netting, wrapping, and discharging, which are electrically controlled devices, were constant and other working times, such as turning time, decreased slightly in the case of rice-straw and IRG (Table 4).

Bale outputs by driving speed were shown to be 30 bales at a driving speed of 2.3 km/h, 36 bales at a driving speed of 3.2 km/h, and 44 bales at a driving speed of 5.1 km/h, and the total weights of bales produced were 6.8 tons, 8.4 tons, and 10.5 tons, respectively, in the case of rye-straw. In the case of rice-straw, bale outputs were shown to be 43, 44, and 48 bales at driving speeds of 4.3 km/h, 5.0 km/hr, and 6.2 km/h, respectively and the total weights of bales produced were 8.8 tons, 9.7 tons, and 10.7 tons, respectively. In the case of IRG, bale outputs were shown to be 35, 37, and 38 bales at driving speeds of 7.0 km/h, 8.3 km/hr. and 9.5 km/h, respectively, and the total weights of bales produced were 10.7 tons, 12.0 tons, and 13.2 tons, respectively. Therefore, when the driving speed increased by 1 km/h under the experimental condition, the number of bales that could be produced increased by 5 in the case of rye-straw, 2.6 in the case of rice-straw, and 1.2 in the case of IRG. The average weights of bales produced in the entire experimental section were shown to be 234.7 kg, 216.5 kg, and 328.0 kg for rye-straw, rice-straw, and IRG, respectively. According to the experimental results, as the driving speeds increased by 3.2 km/h in the case of rye-straw, 2.9 km/h in the case of rice-straw, and 2.5 km/h in the case of IRG, the total weights of the bales increased by 2.4%, 10.0%, and 12.4%, respectively, and the diameters increased by 2.8%, 3.2%, and 2.9%, respectively. In addition, as the driving speed increased, the working distance for the driver to respond to the bale success sensor was shown to increase.

Examination of residue ratios

The residue ratios at the three levels of tractor driving speeds were as follows: rye-straw ranged from 2.47% to 2.82% (average 2.61%), rice-straw ranged from 1.75% to 2.05% (average 1.89%), and IRG ranged from 1.50% to 1.65% (average 1.57%). As the driving speed increased, the residue ratios increased slightly: rye-straw increased by 0.35%, rice-straw increased by 0.27%, and IRG increased by 0.28%. However, these differences were not statistically significant (Table 5).

To analyze the collectability of the harvester's pick-up operations, residues were collected and analyzed in three levels: longer than 500 mm, 200 mm to 500 mm, and shorter than 200 mm. The forage can be entirely collected when the length is longer than 500 mm, and it can be partially collected when the length is 200 mm to 500 mm; however, it cannot be collected when the length is shorter than 200 mm. Most of the residues were those shorter

Table 5. Residue ratio changes in accordance with changes in the driving speed (kg/bale)

Forage crop		Rye-straw			Rice-straw			IRG		
Driving speed (km/h)*		2.3	3.2	5.1	4.3	5.0	6.2	7.0	8.3	9.5
Residue* (kg)	>500 mm	0.36	0.37	0.42	0.21	0.25	0.29	0.22	0.27	0.32
	200–500 mm	1.45	1.56	1.66	0.37	0.44	0.52	0.88	1.16	1.38
	<200 mm	4.08	4.02	4.63	2.99	3.44	3.80	3.54	3.98	4.49
	Total	5.89	5.95	6.71	3.57	4.13	4.61	4.64	5.41	6.19
Residues ratio (%)**		2.47	2.55	2.82	1.75	1.88	2.05	1.50	1.65	1.78

* This category represents average residue length of samples at each level
** The residues ratio is obtained by adding the average value for each process

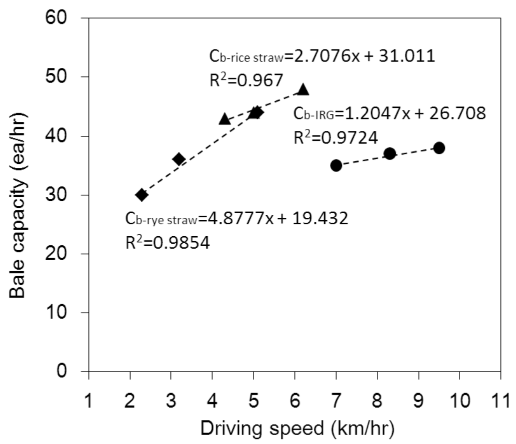


Figure 6. Relations between driving speed and bale output.

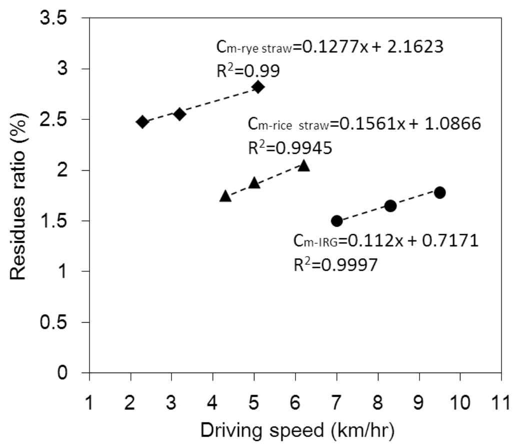


Figure 7. Relations between driving speed and residue ratios.

than 200 mm, which cannot be collected, and they were generated during mowing with the disc-mower, collecting with the hay-rake machine, and pick-up with the harvester. The ratios were at least 66%, and the average ratios were 68.57% in the case of rye-straw, 83.13% in the case of rice-straw, and 74.14% in the case of IRG. The ratios of 200 mm- to 500 mm-long residues, which can be partially collected, ranged from 10% to 26%.

To comprehensively analyze the bale production performance of the harvester, the trends of changes in bale outputs (Figure 6) and residue ratios (Figure 7) are shown. As the driving speed increased, bale outputs and residue ratios increased proportionally. In the case of rye-straw, when the bale outputs increased by 46.7%, the residue ratios increased by 14.2%. In the case of rice-straw, when the bale outputs increased by 11.6%, the residue ratios increased by 17.1%. In the case of IRG, when the bale outputs increased by 8.6%, the residue ratios increased by 18.7%. The ratios of residues not picked up by the harvester ranged from 1.5% to 2.8% of the available quantities, and the residue ratios—excluding those residues that are shorter than 200 mm—were even better, being lower than 1.0%. In addition, increases in the driving speeds were closely correlated with increases in residue ratios, with correlation coefficients exceeding 0.99, but the absolute weights of the residue increments were insignificant.

Conclusions

In this study, an integrated forage harvester was developed that can be attached to 90ps-tractors commonly used at stockbreeding farmhouses. It was developed and fabricated so that both bale harvesting and vinyl wrapping were integrated and could be done using a single tractor. Field adaptation experiments of the fabricated harvester were conducted. According to the experimental results, the bale outputs (i.e., total weights) per hour by driving speed shown by the harvester were 30 bales (6.8 MT) at 2.3 km/h, 36 bales (8.4 MT) at 3.2 km/h, and 44 bales (10.5 MT) at 5.1 km/h in the case of rye-straw. In the case of rice-straw, they were 43 bales (8.8 MT) at 4.3 km/h, 44 bales (9.7 MT) at 5.0 km/h, 48 bales (10.7 MT) at 6.2 km/h. In the case of IRG, they were 35 bales (10.7 MT) at 7.0 km/h, 37 bales (12.0 MT) at 8.3 km/h, and 38 bales (13.2 MT) at 9.5 km/h. In addition, the residue ratios at three levels of driving speeds were as follows: rye-straw ranged from 2.47% to 2.82% (average 2.61%), rice-straw ranged from 1.75% to 2.05% (average 1.89%), and IRG ranged from 1.50% to 1.65% (average 1.57%). According to the results of the analysis, as the driving speeds increased, the residue ratios increased by 0.35% in the case of rye-straw, 0.27% in the case of rice-straw, and 0.28% in the case of IRG, but these differences were not significant. In addition, the residue ratios—excluding those residues that were shorter than 200 mm, which cannot be practically collected—were as also good, being lower than 1.0%. It could be seen that bale production by the harvester implemented after raking showed larger collecting weights per unit area, indicating that the production capacity had been drastically improved. Since the baling and wrapping functions, which had been separately operated, were integrated into each unit of the integrated forage harvester developed in this study, it is expected to maximize bale production efficiency and greatly contribute to the improvement of labor productivity.

Conflict of Interest

The authors have no conflicting financial or other interests.

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