International Journal of Technology (2016) 7: 1222-1231
ISSN 2086-9614

A STUDY ON SIZE REDUCTION OF EUCALYPTUS BARK FROM THE PROCESSING INDUSTRY FOR PRODUCING BIOMASS PELLETS

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(Received: July 2016 / Revised: October 2016 / Accepted: October 2016)

ABSTRACT

Recently, there was an increase in demand of biomass pellets as an alternative energy source. However, it is necessary to reduce the size of granular materials during the pelleting process. The size reduction of eucalyptus bark occurs in the industrial processing of biomass pellets production, using a hammer mill together with three sieve sizes of 3, 4, and 5 mm and the sieve speeds of 900, 1000, 1100, and 1200 rpm, respectively, which have been examined at a feed rate of 80 kg/h. The aims of this study were to determine the important parameters, namely rotational speed, to determine suitable sieve size for reducing the size of eucalyptus bark, and to analyze energy usage in the size reduction process by using a hammer mill. The results have shown that using a 5 mm sieve size at 900 rpm sieve speed resulted in the best operating conditions in order to offer the highest capacity and lowest specific energy consumption. Moreover, the average particle size of 0.15 mm was an acceptable value. This study could be very beneficial in the development process to produce biomass pellets.

Keywords: Biomass; Eucalyptus bark; Hammer mill

1. INTRODUCTION

Eucalyptus (E. *camaldulensis*, etc.) is an important crop and is one of the main raw materials for the paper production industry. The demand of eucalyptus wood for the paper industry in Thailand is millions tons per year. Most of the wood chip industry utilizes chopped eucalyptus wood and thus, produces paper pulp by machine (Borisuttipongsakul, 2013). In the paper industry, eucalyptus wood, as a raw material, consumes about 100 tons/day to produce waste, which can be applied in several ways, for example, making compost and applying fertilizer for growing crops or producing biomass and so on (Luangtrirat et al., 2014).

Biomass pellets are made by transforming the waste material from agriculture or related industries into useful biomass which can be used as raw materials in thermal power plants for electricity generation **(**Ministry Energy of Thailand, 2011). The process for producing biomass pellets has several stages. First step is the size reduction of unsuitable raw material. This is an important step for the production of biomass pellets as raw materials to make products with consistent quality. If the material is too small or too large, it will affect the quality of products, increase the power consumption of pellet production and pellets can cause damage, due to the

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Permalink/DOI: https://doi.org/10.14716/ijtech.v7i7.4740

size of the raw material (Wiriyaumpaiwong et al., 2005). If the moisture content of the materials is not suitable for the pellets in terms of tabletability, the pellets require a further drying step. Then, the pellets should be mixed either with other raw materials, or by using only one type of material. According to the Plastics Institute of Thailand (2013), to form biomass into pellets, it is necessary to place a pellet through a hub of 6:37 to 7:25 millimeters in length (or 0.250 to 0.285 inches) and then the dry biomass pellets before distribution (PFI, 2008; Plastics Institute of Thailand, 2013). Accordingly, the manufacturing process includes several steps and this causes a high demand in energy consumption. The energy used can be considered from two processes, first the energy for reducing the raw material size and second, for the pelleting process.

The eucalyptus bark is biomass material leftover from the paper and wood processing industry, which can be used to produce biomass pellets. However, the existing eucalyptus bark from the industry is not in a suitable form to produce biomass pellets. Thus, the step of size reduction of the bark using a hammer mill is of importance before the pelleting process can occur. To the best of our knowledge, the information about size reduction of eucalyptus bark and also those factors related to downsizing have not been studied in depth. So, the objectives of this research are to investigate these important parameters, such as rotational speed, suitable sieve size for reducing the size of eucalyptus bark, and analysis of energy usage consumed in the size reduction process by a hammer mill.

2. METHODOLOGY

2.1. Material

The materials used in this study were eucalyptus bark received from the paper industry in Khon Kaen, Thailand. The average moisture content of the bark is 10.50% wb. The moisture content of wood charcoal powder was determined using ASAE S358 method (ASAE, 2003).

2.2. Measurement of Physical Properties of Eucalyptus Bark

2.2.1. Moisture content

The moisture content of eucalyptus bark was determined using ASAE S358 (Wiriyaumpaiwong, 2005; ASAE, 2003), where 25 g samples of material were oven-dried at 105^{o}C for 24 h. All of the moisture content tests were performed in replicates of three.

2.2.2. Bulk density of eucalyptus bark

Bulk density of eucalyptus bark at a moisture content of 10.50% wb was determined by carefully filling the sample in a standard 0.5 m^3 cylindrical container (Kurjak, 2005). After filling every third portion of the container with eucalyptus bark samples, the container was tapped on a wooden table, at approximately ten times to allow the material to settle down. After completely filling the container, excess material at the top was removed by moving a steel roller. The mass per unit volume gave the bulk density of the charcoal in kg/m^3. All of the bulk density tests were performed in replicates of ten.

2.2.3. Static coefficient of friction

The static coefficient of friction for eucalyptus bark was measured using a friction device against five structural materials: plywood, mild steel, plastic, rubber and zinc (Kaliniewicz, 2013; Sirisomboona et al., 2007).

2.3. Thermal Properties of Eucalyptus Bark

2.3.1. Proximate analysis

The proximate analysis method was often used to determine chemical properties of biomass fuel materials for contents of moisture, volatile material, ashes and fixed carbon, and these were tested in laboratories, according to ASTM standard D5373-02 (ASTM, 2003).

2.3.2. Ultimate analysis

The ultimate analysis method is an analysis of the fuel components used in the determination of the heat of combustion, reported as a percentage of the elements, which consist of carbon, hydrogen, nitrogen, oxygen, sulfur and chlorine (ASTM, 2003).

2.3.3. Heating values

The heating value of charcoal feed stocks indicates the energy processed as potential fuels. An oxygen bomb calorimeter (Art.2060/2070) with an accuracy of 0.0001°C was used to determine the heating value of charcoal in MJ/kg The calculation of gross calorific value of coal and coke was based on ASTM Standard D5865-03 (ASTM, 2003)

2.4. Size Reduction

To reduce biomass size, a hammer mill (KKU-2015) was used, one which had 42 swinging hammers attached to a shaft, (powered by a 5 hp electric motor), subsequently grinding the bark for the size reduction. For the test, three different sieve sizes: 3, 4, and 5 mm and four levels of hammer mill drum speed, allowed to rotate at: 900, 1000, 1100, and 1200 rpm, respectively were used to operate in the experiment (Figure 1). This experiment used a feed rate of 80 kg/h for the testing. The performance indicators used for evaluation were the output capacity, specific energy consumption and geometric mean diameter.

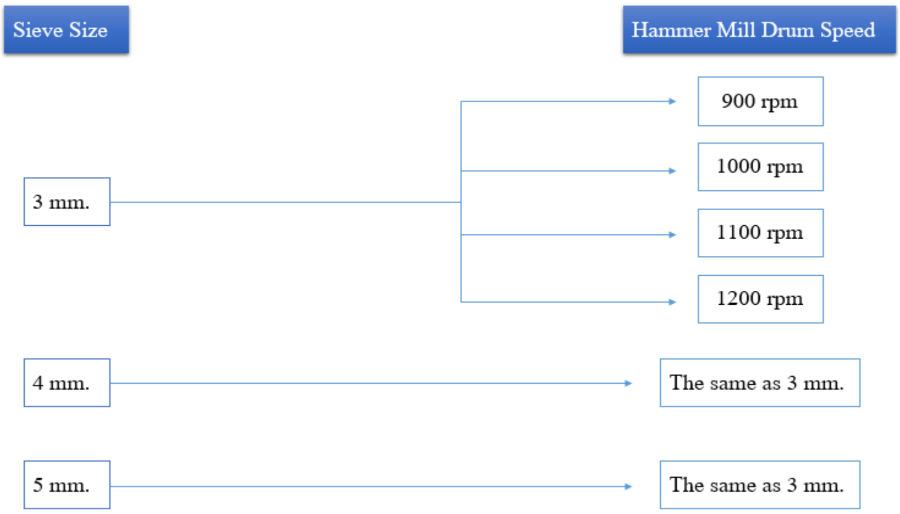

Figure 1 Factorial experiment setup

2.4.1. Analysis of the capacity of the hammer mill

To analyze the capacity of the hammer mill in size reduction of eucalyptus bark, the process was conducted by sampling all treatments and measuring the time using a stopwatch during the sampling. Then the work capacity was calculated.

2.4.2. Analysis of specific energy in electricity consumption

The analysis of specific energy in electricity consumption of the hammer mill for size reduction of the eucalyptus bark was performed by using a device to measure electrical current (multimeter) AC / DC RMS + W Clamp meter Brand: Chauvin Arnoux. This machine was connected to the power supply of an inverter and used a video recorder to measure the electrical current. Then, the aimed value was calculated according to Equation 1, (Ministry Energy of Thailand, 2009).

$$\text{Specific Energy Consumption index,} \quad SEC = \frac{\text{Energy Consumption}}{\text{Production quantity}} \tag{1}$$

2.4.3. Analysis of the eucalyptus bark after size reduction

Particle size analysis of the eucalyptus bark after size reduction involved a Ro-Tab sieve shaker (W.S. Tyler Inc., Mentor, OH). A 200 g sample of eucalyptus bark through size reduction from the three sieves for each speed was poured on the first floor of the shaker sieve; it took five minutes to shake. Then it was weighed and the backlog percentage for sieve size 7 layers of 4.75 mm, 1 mm, 0.590 mm, 425 µm, 250 µm, 150 µm, and 75 µm, respectively was calculated. Then, the geometric mean diameter was calculated using a ASAE S319.2 method (Chevanan et al., 2008). The geometric mean diameter (d_{gw}) of the sample was calculated according to Equation 2 (Addo et al., 2012).

$$d_{gw} = log^{-1}[\frac{\Sigma(W_i logd_i}{\Sigma W_i}] \quad (2)$$

2.5. Statistical Analysis

The data was analyzed by the statistical analysis plan to test a 3×4 Factorial Experiment in a completely randomized design (CRD) analysis of variance. A comparison between pairs of treatment means was made by determining the least significant difference (LSD) at 5% significance for sieve size and appropriate speed of the hammer mill (Oehlert, 2010; Gomez & Gomez, 1984).

3. RESULTS

3.1. Physical Properties of Eucalyptus Bark

The moisture content of eucalyptus bark was determined using ASAE S358 (ASAE, 2003), where 25 g samples of material were oven-dried at 105^{o}C for 24 h at 10.50% (wb) (Table 1) and had a bulk density average of 651.04 kg/m^3. The static friction coefficient of eucalyptus bark on a plywood, mild steel, plastic, rubber and zinc average of 0.60, 0.55, 0.40, 0.65, and 0.52 respectively while the angle of repose was an average of 61.8 degrees.

Table 1 Physical properties of eucalyptus bark

Properties	Eucalyptus Bark
Physical properties	
Moisture content % (wb)	10.50
Bulk density (kg/m^3)	651.04
Coefficient of static friction on various surfaces:	
- plywood	0.60
- mild steel	0.55
- plastic	0.40
- rubber	0.65
- zinc	0.52
Angle of repose (degrees)	61.8

3.2. Thermal Properties of Eucalyptus Bark

The proximate analysis of eucalyptus bark powder is shown in Table 2, evaluating as follows: moisture content, volatile material, fixed carbon and ashes of 10.50, 69.50, 11.03, and 8.97 percent respectively. The ultimate analysis of eucalyptus bark powder samples had carbon, hydrogen, nitrogen, oxygen, sulfur and chlorine of 38.102, 6.113, 0.248, 44.180, n.d. (not defined), and 0.04 percent, respectively, and the heating value was at 3625.37 kcal/kg.

Table 2 Thermal properties of eucalyptus bark

Properties	Eucalyptus bark
Proximate analysis	
moisture contents (%)	10.50
volatile material (%)	69.50
fixed carbon (%)	11.03
ashes (%)	8.97
Ultimate analysis	
carbon (%)	38.102
hydrogen (%)	6.113
nitrogen (%)	0.248
oxygen (%)	44.180
sulfur (%)	n.d.
chlorine (%)	0.04
heating value (kcal/kg)	3625.37

The size reduction test for the eucalyptus bark by a hammer mill was performed at a constant rate of 80 kg/h and a sieve of three different sizes of 3, 4, and 5 mm, respectively. Hammer mill testing of each rack was tested at four speeds of 900, 1000, 1100, and 1200 rpm, respectively to determine the capacity of the hammer mill. It can be seen from the graphs that the 3 mm sieve size with speeds at 900, 1000, 1100, and 1200 rpm, gave capacities of 29.64, 28.09, 35.24, and 35.05 kg/h, respectively. The 4 mm sieve size with speeds at 900, 1000, 1100, and 1200 rpm gave capacities of 31.01, 32.41, 35.74, and 37.89 kg/h, respectively. The 5 mm sieve size with speeds at 900, 1000, 1100, and 1200 rpm gave capacities of 51.39, 49.08, 49.34, and 47.16 kg/h, respectively (Figure 2).

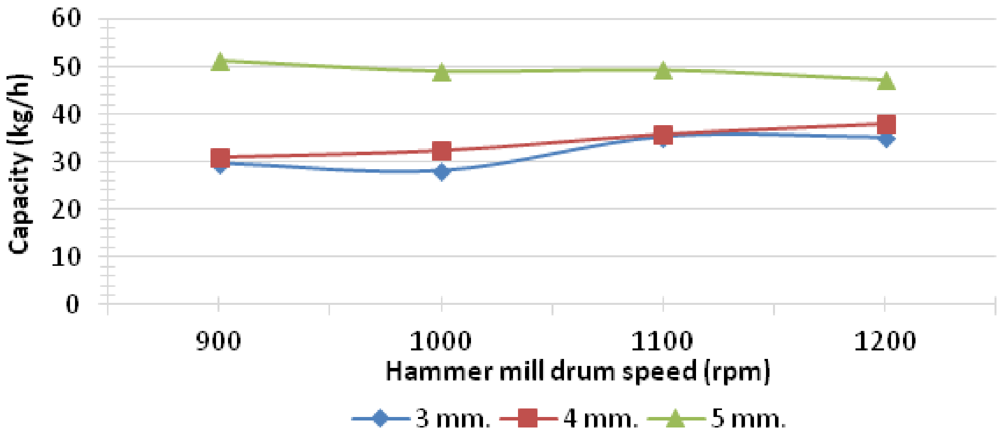

Figure 2 Relationship between hammer mill drum speed and its capacity

The analysis of specific energy consumption for size reduction of the eucalyptus bark was calculated by using Equation 1. The data indicated that at different speeds of 900, 1000, 1100, and 1200 rpm, for 3 mm sieve size, electricity power consumption increased with specific energy at 17.08, 18.23, 19.49, and 23.128 watt-h/kg, respectively. On the other hand, for the 4 mm sieve size, specific energy decreased at 20.78, 19.36, 17.84, and 16.36 watt-h/kg, respectively, and for the 5 mm sieve size, specific energy decreased slightly at 12.61, 12.69, 12.97, and 13.20 watt-h/kg, respectively (Figure 3).

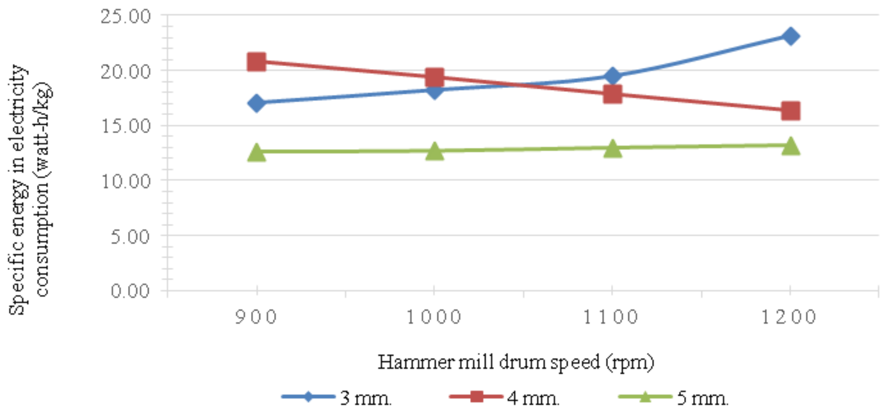

Figure 3 Relationship between hammer mill drum speed and its specific energy consumption on eucalyptus

The analysis of eucalyptus bark particle size after size reduction, according to Equation 2, for the 3 sieve sizes of 3 mm, 4 mm, and 5 mm, through the use of 7 layers of sieve sizes of 4.75 mm, 1 mm, 0.590 mm, 425 µm, 250 µm, 150 µm, and 75 µm and the 4 testing speeds of 900, 1000, 1100, and 1200 rpm, respectively gave the following results. For the 3 mm sieve size and increasing speed, while the average particle size remained quite constant at 0.022, 0.023, 0.023, and 0.027 mm, respectively, whereas for the 4 mm sieve size and increasing speed the average particle size had a decreasing trend at 0.133, 0.121, 0.095, and 0.095 mm, respectively, and for the 5 mm sieve size and increasing speed the average particle size had mixed trends at 0.15, 0.17, 0.21, and 0.19 mm, respectively (Figure 4).

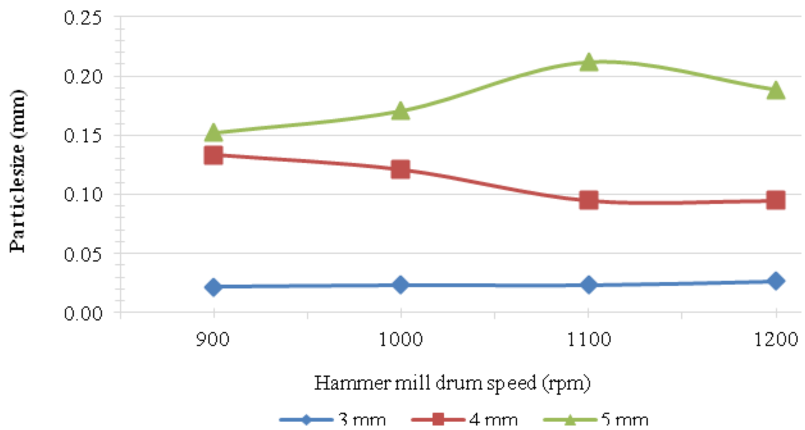

Figure 4 Relationship between the hammer mill drum speed and its particle size on eucalyptus

4. DISCUSSION

The analysis of variance (ANOVA) shown in Table 3 indicated that the sieve size (B) significantly affected capacity, specific energy consumption and geometric mean diameter of eucalyptus bark particles, but the hammer mill drum speed (A) did not significantly affect capacity, specific energy consumption and geometric mean diameter of eucalyptus bark particle. The first-order interaction (A×B) did not have any significant effect on any of the 3 indicators.

Table 3 ANOVA: Effects of sieve size and hammer mill drum speed on performance of the hammer mill experimental unit

SOV	f-value			
	df	capacity	energy	Paricle size
rpm (A)	3	0.51n.s.	0.03n.s.	0.21n.s.
sieve size (B)	2	42.7**	95.12**	100.65**
A×B	6	1.24n.s.	2.41n.s.	2.22n.s.
Error	24			
Total	35			

** Highly significant at 1% level; * significant at 5% level; n.s.: non-significant; df : degrees of freedom

4.1. Effect of Sieve Size and Hammer Mill Drum Speed on Capacity

The statistical analysis of data and comparing the average capacity (Table 4), which shows a comparison of the average capacity, found that speed does not affect the capacity difference statistically, but the sieve size has affected capacity in a different way statistically (Figure 3) The analysis exposed that when the speed increased from 900 to 1200 rpm, the 5 mm sieve size is more capable than other sieve sizes, corresponding to the average capacity of 49.24 kg/h. A minor 4 mm sieve size with the same capacity had a capacity at an average of 34.26 kg/h. The 3 mm sieve size with the ability to work was below that of the other sieve sizes. The 3 mm seize size had a capacity at an average of 32.01 kg/h. It is clear that the pit of the sieves size was different, which would have an effect on the capacity at different times. This was similar to the findings in the size reduction of barley by Al-Rabadi (2003) using sieve size 2 and 6 mm at 1140 rpm in that the capacity increased with sieve size.

Table 4 Comparison of capacities (kg/h) for varying sieve size and hammer mill drum speed

Sieve size (mm)	Hammer mill drum speed (rpm)				Avg.
	900	1000	1100	1200	
3	29.64	28.09	35.24	35.05	32.01c
4	31.01	32.41	35.74	37.89	34.26b
5	51.39	49.08	49.34	47.16	49.24a
$LSD_{24,0.05}$	1.77 kg/h				

Mean in column followed by the same letter are not significantly different at 95% confidence level

4.2. Effect of Sieve Size and Hammer Mill Drum Speed on Specific Energy Consumption

The statistical analysis of data and comparison of the average specific energy consumption (Table 5) showed that speed did not significantly affect specific energy consumption, which was similar to the findings of Bitra et al. (2008) who argued that the tangential velocity of hammer mill increased slightly with power consumed, but sieve size had significant effect on specific energy consumption as shown in Figure 3. It indicated that when speed increased from 900 to 1200 rpm, the 3 mm sieve size significantly gave higher specific energy consumption than the other two sieve sizes, with an average value of 19.14 watt-hour/kg. The 4 mm sieve size gave a lower specific energy consumption of 16.34 watt-h/kg, while the 5 mm sieve size gave the lowest specific energy consumption of 11.79 watt-h/kg. To sum up, because the sieve size of 3 mm was of smallest size, it could cause accumulation of the eucalyptus bark particles in the hammers of the mill. As a result of this, the power consumption was high. This was similar to the findings on size reduction barley of Al-Rabadi (2008) using sieve sizes of 2 and 6 mm at 1140 rpm.

Table 5 Comparison of specific energy consumptions (watt-h/kg) for varying sieve size and hammer mill drum speed

Sieve size (mm)	Hammer mill drum speed (rpm)				Avg.
	900	1000	1100	1200	
3	18.06	16.29	19.08	23.12	19.14c
4	17.78	16.23	17.01	14.34	16.34b
5	9.96	10.53	14.13	12.55	11.79a
$LSD_{24,0.05}$	1.007 watt-h/kg				

Mean in column followed by the same letter are not significantly different at 95% confidence level

4.3. Effect of Sieve Size and Hammer Mill Drum Speed on Particle Size

The statistical analysis of data and comparison of the average particle size (Table 6) showed that speed did not significantly affect particle size, but sieve size had a significant effect on particle size, as also shown in Figure 4. It indicated that when the speed increased from 900 to 1200 rpm, the 3 mm sieve size significantly gave a lower particle size than the other two sieve sizes, with an average value of 0.024 mm. The 4 mm sieve size gave a higher average particle size of 0.111 mm, while the 5 mm sieve size gave the highest average particle size of 0.188 mm. This was similar to the findings on size reduction barley of Al-Rabadi (2003) and corn of Wondra et al. (1995).

Table 6 Comparison of particle size (mm) for varying sieve size and hammer mill drum speed

Sieve size (mm)	Hammer mill drum speed (rpm)				Avg.
	900	1000	1100	1200	
3	0.022	0.023	0.023	0.027	0.024c
4	0.133	0.121	0.095	0.095	0.111b
5	0.152	0.171	0.212	0.188	0.188a
$LSD_{24,0.05}$	0.037 mm				

Mean in column followed by the same letter are not significantly different at 95% confidence level

5. CONCLUSION

The study on size reduction of eucalyptus bark from the paper industry for producing biomass pellets is summarized as follows: the 3 mm sieve size had an appropriate speed of 1100 rpm to give a capacity of 35.24 kg/h, the particle size distribution within the hammer milling speeds was better than the other two sieve sizes with a specific power consumption of 19.49 watt-h/kg. The 4 mm sieve size with the hammer milling speed of 1200 rpm gives a capacity of 37.89 kg/h, a particle size of medium suitability and a specific power consumption of 16.36 watt-h/kg. The 5 mm sieve size had an appropriate speed of 900 rpm due to a given capacity of 51.39 kg/h. This average work rate was the highest among the three conditions of sieve size, while the specific power consumption was the lowest, 12.61 watt-h/kg. The statistical analyses showed that for the increase of speed from 900 rpm to 1200 rpm, the 5 mm sieve size would have a better advantage over the 4 mm and 3 mm sieve sizes in which the obtained capacity was the highest, while the specific power consumption was the lowest. On the other hand, although the average particle size was highest among the three, this value would be quite acceptable in the biomass pelleting industry and therefore, the 5 mm sieve size can be used to develop the pellet process and reduce energy consumption in the production of biomass pellets.

6. ACKNOWLEDGEMENT

This work was financial supported by the young researcher development project of Khon Kean University. The researchers would like to thank the Agricultural Machinery and Postharvest Technology Center, Khon Kaen University and Postharvest Technology Innovation Center, and the Commission on Higher Education, Bangkok for generously supporting this research and testing.

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