Engineering Journal issn: 0125-8281

Article

Design and Evaluation of a Small Axial Flow Sunflower Thresher Unit

Pisal Muenkaew[1,2,a]**, Somchai Chuan-Udom**[1,b,*]**, and Anuwat Pachanawan**[3,c]

1 Department of Agricultural Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand
2 Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen 40000, Thailand
3 Rajamangala University of Technology Twan-ok University, Chonburi Province, Chonburi 20110, Thailand
E-mail: [a]mpisal@kkumail.com, [b,*]somchai.chuan@gmail.com (Corresponding author), [c]anuwat_pa@rmutto.ac.th

Abstract The design of a small axial flow sunflower thresher for tractor installation needs to be developed and evaluated to obtain performance data suitable for sunflower seed production in Thailand. Therefore, the purpose of this research is to design and evaluate a small axial flow sunflower thresher. The design of this unit was done according to the concept of a plant thresher machine, which consists of a set of rotor drums and threshing sieves. The performance of the small axial flow sunflower thresher was evaluated in terms of sunflower moisture in the range of 8.92 to 21.72%, feed rate in the range of 800 to 1,600 kg/h, and linear rotor speed of spike-teeth in the range of 6 to 14 m/s. Evaluation of the threshing unit showed that these three factors had a statistically significant effect on sunflower threshing performance. The optimal parameters to achieve maximal performance are as follows. First, the sunflower moisture content should be in the range of 12 to 14% on a wet basis. Second, the feed rate should be in the range of 1,000 to 1,200 kg/h. Last, the linear velocity of the threshing rotor should range from 10 to 12 m/s. This will achieve greater than 98% threshing efficiency with threshing losses and grain breakage of less than 2%. Future research should investigate additional factors influencing the separation and cleaning of axial flow sunflower thresher machines.

Keywords: Sunflower, small axial flow thresher, axial flow thresher, thresher performance.

ENGINEERING JOURNAL Volume 28 Issue 4
Received 19 August 2023
Accepted 19 April 2024
Published 30 April 2024
Online at https://engj.org/
DOI:10.4186/ej.2024.28.4.51

DOI:10.4186/ej.2024.28.4.51

1. Introduction

Sunflowers are one of the most important cash crops in the world's food and health industries [1-4] because they contain a variety of nutrients that are beneficial to the human body [5]. Sunflowers are short-lived plants that are easily grown. They are widely planted for production and distribution in Asia, Australia, the Americas, and some parts of Europe. Currently, sunflowers are planted in more than 80 countries, with Ukraine and Russia being the main producers in the world, with a total output of about 33 million metric tons per year [6]. However, the conflict between these countries has resulted in reduced output. This has led to insufficient production to meet the needs of the industry, affecting importing countries, such as Thailand, since the country's demand for sunflowers exceeds its domestic production. In 2021–2022, Thailand produced 1,291 metric tons of sunflower seeds, which is insufficient to meet the needs of its domestic food industry [7].

In most sunflower production in Thailand, farmers prefer to use large machinery for harvesting since this is convenient and rapid. However, from survey information in sunflower-growing areas, it was found that combine harvesters are not very suitable for harvesting sunflowers. At harvest time, farmers will adapt their threshing machines to suit the crop because the machinery used by farmers to harvest sunflowers is also used to harvest other crops. This is the main cause of seed losses. If farmers want to reduce production costs, they must reduce harvest costs because this is the most expensive step in the entire production process [8–18]. Numerous researchers have developed machines that can be used with a variety of Thai crops and small-area crop planting to reduce costs incurred in sunflower harvesting [19–23]. Therefore, the most suitable tools are small machines that can be attached to tractors to increase their utilization [21, 24–25].

The threshing unit is central in the harvesting process. Most threshing machines in Asia have spike-tooth threshing balls, which are adapted from other threshing units [26]. It is necessary to have a small, light, and simple design for maintenance and for mounting on a tractor [21]. In a research study of small plant threshing machines with threshing balls less than 3 feet in size, it was found that spike-tooth clearance and concave clearance had a significant effect on threshing [27]. In 2017, Wuttiphol Chansrakoo et al. studied the factors affecting the performance of a small axial flow soybean thresher. They found that the concave clearance, peg-tooth clearance, guide vanes, rotor speed, and feed rate affect threshing performance [28]. In 2016, Waree Srison studied the designed factors affecting losses in axial flow corn threshers. The results showed that concave clearance, peg tooth clearance, and concave rod clearance had a statistically significant effect on threshing losses [19]. In 2022, Pisal et al. studied the design factors of a sunflower threshing unit. They chose a spike tooth that was suitable for sunflower threshing. The influence of concave clearance and peg-tooth clearance had a significant effect on sunflower threshing performance [27]. The current research will involve mounting a threshing unit on a small tractor.

According to research on design of small sunflower threshing units, mounting spike-teeth on a rotor threshing unit will result in higher performance. These parameters should be adjusted so that concave clearance is 5 to 10 mm with a spike-tooth clearance of 125 to 150 mm, and concave rod separation in the range of 20 to 25 mm. Sunflower losses and broken seed percentages were less than 2%, while threshing efficiency was 95% or more [27]. The above research suggests that a small axial flow threshing unit can effectively thresh sunflowers. Previous research studies only considered the design factors affecting sunflower threshing performance in the laboratory. However, construction and performance evaluation of a small axial-flow sunflower threshing unit has not been done. Therefore, in this research, a small axial flow sunflower threshing unit was developed to evaluate the performance of the unit and determine whether it is suitable for use on a small tractor to yield high threshing performance, low total losses, and few broken grains.

2. Materials and Methods

2.1. The Concept of Designing of Threshing Unit

Threshing units can be classified into several types depending on the working principle of separating the seed from the non-seed parts. Thailand is a country in which small-scale farming is widely done. Small axial flow seed threshers are suitable for threshing seeds [21]. In the principle of axial flow threshing, when passing plants through the feeding port, the rotation of the threshing drum causes the threshing tines to strike the plants and cause them to move into the threshing chamber. Then, the plants are scraped and scrubbed against the threshing sieve, causing the seeds to fall out of their pods. The material is moved by an auger along the threshing axis, causing the plant to be kneaded several times until it is ejected from the threshing chamber. In the threshing process, material smaller than the rod clearance of the threshing sieve will fall through the lower threshing sieve. These materials include seeds that are still attached to the pods. Straw and other contaminants must be sorted and cleaned with further sorting and cleaning equipment. The working characteristics of an axial flow threshing unit are shown in Fig. 1 [22, 29–30].

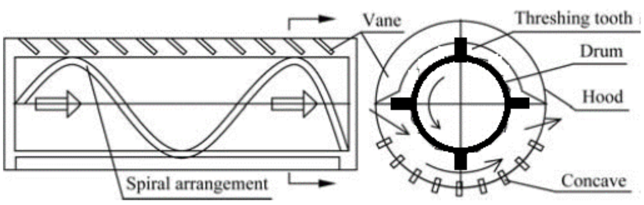

Fig. 1. Axial flow threshing characteristics.

2.1.1. Threshing rotor drum design concept

The threshing rotor drum characteristics of a small axial flow sunflower threshing unit significantly affect performance, especially the shape of the spike-tooth drum. This affects the energy used in the threshing process due to the impact between the teeth and the sunflowers. When the threshing drum rotates, spiked teeth impact the sunflowers within the gap between the threshing tines and the threshing rod. This causes a force to be applied to the sunflowers, as shown in Fig. 2, separating the seeds from the flower disk where they drop through the threshing sieve into the seed tray [22, 31].

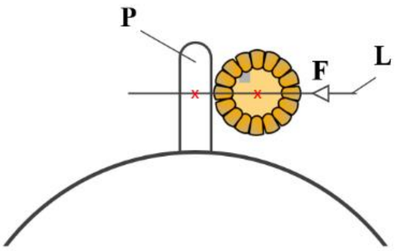

Fig. 2. The acting force between the spike-tooth and the sunflower.

The required threshing unit for these experiments consisted of spiked teeth installed on a threshing rotor drum. This is a cylindrical steel bar attached to a threshing ball where the spike tooth clearance can be adjusted, as shown in Fig. 3. This rotor drum has high threshing efficiency and reduces threshing losses [21].

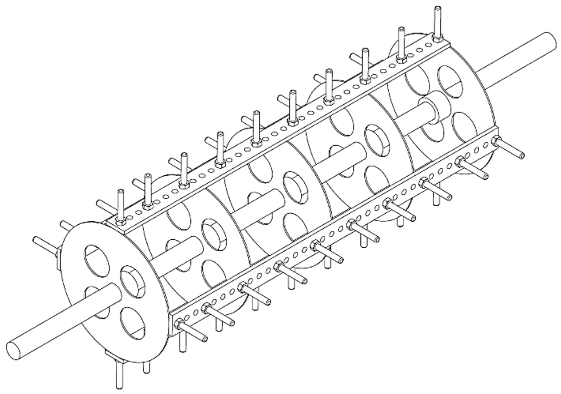

Fig. 3. Structural design of spiked teeth.

2.1.2. Sieve and threshing rod design concept

The characteristics of the sieve are important for the performance of the threshing machine since the shape of the sieve holes depends on the nature and shape of the seeds. The sieve in the threshing unit is responsible for separating the threshed seed from the non-seed parts. If the spacing of the threshing sieves is too far apart, the separation efficiency will likely decrease because many seeds have not yet been threshed and are still attached to the straw. They can easily slip through the threshing sieve but result in less seed damage. The appropriate distance between the sieves depends on the physical characteristics of the seeds [19]. These results indicated that a rod-patterned threshing sieve is suitable for separating sunflower seeds. [27].

2.2. Factors Studied and Experimental Design

This study was to assess the factors affecting the performance of a sunflower threshing unit. Moisture content (MC) was studied at five levels: 8.92, 12.21, 14.30, 18.66, and 21.72%. The feed rate (FR) was at five levels: 800, 1,000, 1,200, 1,400, and 1,600 kg/h. The sequence and linear velocities of five rotor speeds (RS) were 6, 8, 10, 12, and 14 m/s, as shown in Table 1. In experiments examining the effects of MC, FR and RS, the parameter values used are suitable for shelling grain [20, 31, 38]. A central composite design (CCD) experimental plan was formulated, and the effects of each parameter on the coefficients of determination (R^2) were assessed using Design-Expert Software (Version 7; Stat-Ease Inc; Minneapolis, MN, USA.), as shown in Table 2, which can identify many co-factors with suitable locations for use [32].

2.3. Testing Methods

A small axial flow sunflower threshing test was performed using simulated sunflower cutting by a combine harvester. The cut sunflowers were immediately transported and tested in the lab to reduce variability from sunflower deterioration after harvest. The threshing test in each unit used 5 kg of material and a spike-tooth clearance of 125 mm, which is suitable for sunflower threshing [27]. Then, the material that fell through the threshing sieve into the seed trough was collected. This material was ejected through the straw ejection channel, which consists of seed and non-seed parts that were randomly sampled in each experiment. Indicators for analyzing the performance of sunflower threshing include seed losses, seed breakage, power requirements, specific energy consumption, and seed purity.

2.4. Indicating Parameters

The parameters used to evaluate the performance of the sunflower threshing unit were threshing efficiency (TE), threshing loss (TL), grain breakage (GB), power requirements (P), specific energy consumption (SEC), and grain purity (GP). These parameters were calculated based on the Regional Network for Agricultural Machinery (RNAM) test codes [33].

Table 1. Levels of factors studied for the functioning of the sunflower threshing unit.

	Level				
variable	**-2**	**-1**	**0**	**1**	**2**
MC (% wb)	8.92	12.21	14.30	18.66	21.72
FR (kg/h)	800	1,000	1,200	1,400	1,600
RS (m/s)	6	8	10	12	14

Table 2. Central composite design matrix.

Expt. No	MC	FR	RS	Comment
1	-2	0	0	Axial points
2	1	1	1	Factorial point
3	1	1	-1	Factorial point
4	1	-1	-1	Factorial point
5	1	-1	1	Factorial point
6	0	-2	0	Axial points
7	0	2	0	Axial points
8	0	0	-2	Axial points
9	0	0	2	Axial points
10	-1	-1	1	Factorial point
11	-1	-1	-1	Factorial point
12	-1	1	1	Factorial point
13	-1	1	-1	Factorial point
14	2	0	0	Axial points
15	0	0	0	Center points
16	0	0	0	Center points
17	0	0	0	Center points

Threshing efficiency (TE) is the ratio of the weight of sunflower seeds falling through the sieve to the lower support rail and the weight of sunflower seeds leaving the straw ejection channel to the total weight of sunflower seeds fed, as in Eq. (1).

$$\mathrm{TE} = \left(1 - \frac{M_i + M_j}{w_t}\right) \times 100 \quad (1)$$

TE is the threshing efficiency (%), M_i is the weight of sunflower seeds falling through the sieve to the trough (grams), M_j is the weight of sunflower seeds leaving the hay lane (grams), and W_t is the weight of sunflower seeds (grams).

Threshing loss (TL) is the ratio of the weight of the total sunflower seeds exiting at the straw ejection channel and the total weight of sunflower seeds, as shown in Eq. (2).

$$\mathrm{TL} = \frac{W_1}{W_T} \times 100 \quad (2)$$

TL is the threshing loss (%), W_1 is the weight of the total sunflower seeds expelled from the straw ejection channel (grams), and W_t is the weight of the total sunflower seed (grams).

Grain breakage (GB) is the ratio of the weight of broken seeds after threshing at the lower support rail and the total weight of seeds fed to the thresher as shown in Eq. (3).

$$\mathrm{GB} = \frac{M_b}{W_R} \times 100 \quad (3)$$

GB is the broken seeds (%), M_b is the total weight of broken seeds (grams), and W_R is the total weight of seeds from the sample (grams).

The power requirement (P) is the power demand on the electric motor to thresh for 1 second. A three-phase motor is used in this test. P can be expressed as Eq. (4).

$$\mathrm{P} = \sqrt{3} VI \cos \emptyset \quad (4)$$

P represents the power used, in Watts, by the threshing unit. V is the electric potential, I represents electric current, and $\cos \emptyset$ is the power factor.

Specific energy consumption (SEC) is the ratio of electric power to productivity in Watt-hours per metric ton, as shown in Eq. (5).

$$\mathrm{SEC} = \frac{P}{FR} \quad (5)$$

P is power in Watts, and FR is feed rate in metric tons per hour.

Grain purity (GP) is the ratio of the weight of cleaned and threshed sunflower seeds to the total weight of threshed seeds that fell to the trough, expressed as Eq. (6).

$$GP = \frac{P_{pos}}{P_{pre}} \times 100 \quad (6)$$

GP is the percent of seed purity, P_{pos} for the weight of sunflower grain falling through the chute as kernels after cleaning, and P_{pre} is the weight of sunflower grain through chutes as kernels before cleaning.

3. Results and Discussion

3.1. Design of the Sunflower Threshing Unit

The design and refinement of a small axial flow sunflower threshing unit started from the research of Pisal *et al.* (2022). The design concept was to establish an axial flow sunflower threshing unit depicted in Fig. 3. The structure of the threshing unit had dimensions of 1.90 m in length, 1.83 m in width, and 1.60 m in height. It consisted of three main parts. The first is spikes with a tooth clearance of 125 mm. The length and diameter of the threshing rotor drum are 0.93 and 0.36 m, respectively, as shown in Fig. 4. The second part is a threshing sieve made of round steel ribs with a concave rod clearance of 25 mm, as shown in Fig. 5, and a concave-clearance to 10 mm, as shown in Fig. 6. This is the suitable range for sunflower threshing [27]. The last part is a receptacle for the seeds in the threshing process that fall through the threshing sieve. The axial-flow sunflower threshing unit used a five-horsepower electric motor.

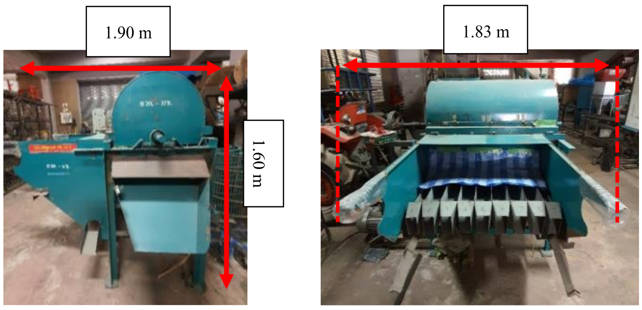

Fig. 3. Small axial flow sunflower threshing unit.

Fig. 4. Spike tooth of the sunflower threshing unit.

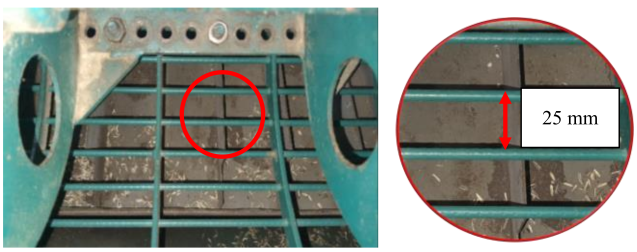

Fig. 5. Concave rod clearance.

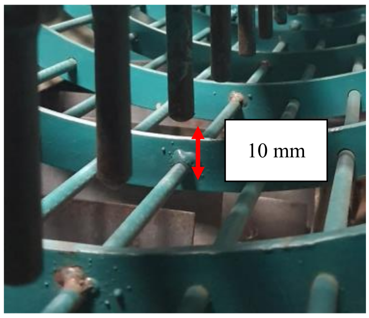

Fig. 6. Concave clearance.

3.2. Evaluation of the Sunflower Threshing Unit

The result of research on the design factors of the small axial flow sunflower threshing unit in the current study showed an optimal feed rate of 1,200 kg/h with a seed moisture content of 14.26%. Spike tooth clearance and concave clearance significantly impact threshing performance. An optimal sunflower threshing process should be set with a concave rod clearance of 25 mm and spike tooth clearance of 125 mm. The concave clearance should not exceed 10 mm [27]. In addition to the effect of the design factors, operation of the small axial flow threshing unit also significantly impacts sunflower threshing performance. These factors include seed moisture content, feed rate, and linear rotor speed. As a result of the current research, it was found that these work factors had a statistically significant effect on sunflower threshing performance. Parameters impacting threshing efficiency (TE) include threshing losses (TL), grain breakage (GB), the required power (P), specific energy consumption (SEC), and grain purity (GP).

3.2.1. Threshing efficiency

Analysis of variance (ANOVA) in linear regression for the design of a small axial flow sunflower threshing unit showed that seed moisture (MC) and linear rotor speed (RS) significantly influenced sunflower threshing efficiency. However, the feed rate (FR) did not significantly impact threshing efficiency. Threshing efficiency tended to increase when the feed rate was reduced, as shown in Table 3.

The regression parameter, lack-of-fit, showed that the analytical equation had a p-value > 0.05. A regression model that predicts the threshing efficiency from an axial flow threshing unit can be expressed as Eq. (7).

$$TE = 98.317 - 0.08MC - 0.465FR + 0.217RS \quad (7)$$

DOI:10.4186/ej.2024.28.4.51

Table 3. Analysis of the variances of TE.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	3.97	3	1.32	11.69	0.0005*
A-MC	1.08	1	1.08	9.52	0.0087
B-FR	0.14	1	0.14	1.22	0.2889
C-RS	2.75	1	2.75	24.34	0.0003
Residual	1.47	13	0.11		
Lack of Fit	1.40	11	0.13	3.86	0.2236ns
Pure Error	0.066	2	0.033		
Cor Total	5.44	16			

ns = Not significant, * = Significant at $p < 0.05$

The result of analysis of variance of the structural equation model and the statistical values affecting the threshing efficiency from an axial threshing unit produced a linear regression with a significantly low p-value (< 0.05). This linear regression had an adjusted R^2 of 0.6673 and a predicted R^2 of 0.4793, as shown in Table 4.

Table 4. Model analysis affecting of TE.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2
Linear	0.0005	0.2236	0.6673	0.4793[1]
2FI	0.8451	0.1808	0.5999	0.1189
Quadratic	0.3981	0.1711	0.6156	-0.3229
Cubic	0.3888	0.1141	0.6986	-8.5524[2]

[1] = Suggested, [2] = Aliased

While Eq. (7) describes response surface methodology (RSM), the relationship between moisture content (MC), feed rate (FR), and linear rotor speed (RS) affected the efficiency of sunflower threshing, as can be seen in Fig. 7. Threshing efficiency was reduced when the rotor speed (RS) increased, and the moisture content (MC) was reduced. This is because the moisture content affects the seeds' capability to adhere to the flower disk as well as their seed hardness [34–36]. Sunflower seeds were better detached from flower disks at higher rotor speeds [21, 31, 37]. Concurrently, when the moisture content was reduced, the threshing efficiency tended to be higher. This agrees with the results of Pachanawan, A. et al. [31].

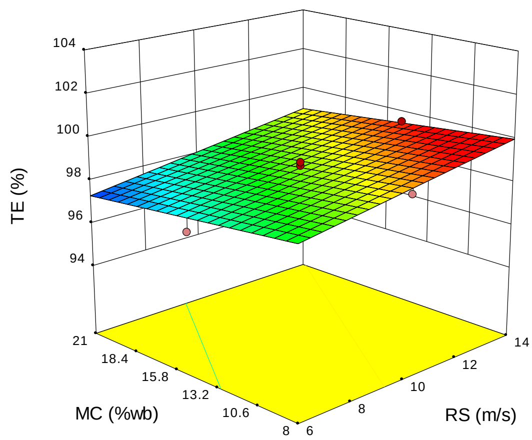

Fig. 7. Graphical response surface of factors affecting TE.

3.2.2. Threshing losses

Analysis of variance (ANOVA) in linear regression for the design of a small axial flow sunflower threshing unit was done. It was found that seed moisture (MC) and linear rotor speed (RS) significantly influenced sunflower threshing losses. The feed rate (FR) did not significantly affect threshing losses, as shown in Table 5.

Table 5. Analysis of the variances of TL.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	6.39	3	2.13	17.27	< 0.0001*
A-MC	1.26	1	1.26	10.18	0.0071
B-FR	0.033	1	0.033	0.27	0.6125
C-RS	5.10	1	5.10	41.37	< 0.0001
Residual	1.60	13	0.12	1.44	
Lack of Fit	1.42	11	0.13	17.27	0.4801ns
Pure Error	0.18	2	0.090		
Cor Total	8.00	16			

ns = Not significant, * = Significant at $p < 0.05$

Examining the lack-of-fit, it was found that the analytical equation had a p-value > 0.05. Therefore, a regression model that predicts the percent loss from an axial flow threshing unit can be expressed as Eq. (8).

$$TL = 3.497 - 0.086MC + 0.228FR - 0.282RS \qquad (8)$$

This linear relationship had a significantly low p-value (< 0.05) with an adjusted R^2 of 0.7531 and a predicted R^2 of 0.6394, as shown in Table 6.

Table 6. Model analysis affecting of TL.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2
Linear	< 0.0001	0.4801	0.7531	0.6394[1]
2FI	0.7695	0.4136	0.7119	0.4425
Quadratic	0.2707	0.4475	0.7567	0.2624
Cubic	0.3949	0.3844	0.8068	-1.9955[2]

[1] = Suggested, [2] = Aliased

While Eq. (8) describes the response surface methodology (RSM), the relationship between moisture content (MC) and linear rotor speed (RS) affected the threshing losses of sunflowers, as can be seen in Fig. 8. As the rotor speed (RS) increases, the losses decrease. With a higher rotor speed, the force applied to the sunflower disk will be greater, resulting in better and faster sunflower seed release, with a concurrent reduction in total losses [35, 38]. During the threshing process at higher moisture contents, fewer seeds fall off the flower disk. Since moisture content affects the capability of the sunflower seeds to remain attached to the flower disk and seed hardness [34–36], more unthreshed seeds are expelled from the high ejection chamber. This results in higher total losses [21, 31, 37], agreeing with the results of Pachanawan, A. et al. [31].

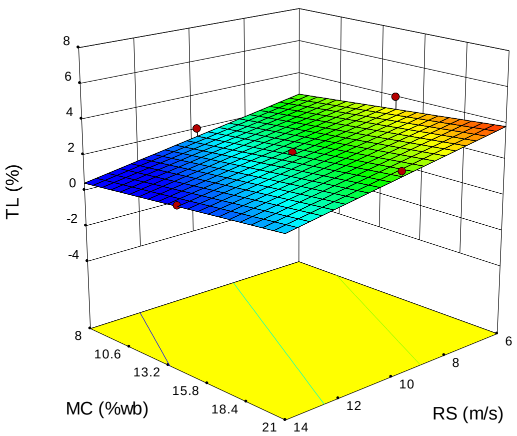

Fig. 8. Graphical response surface of factors affecting TL.

3.2.3. Grain breakage

Analysis of variance (ANOVA) was done for a linear regression in the design of a small axial flow sunflower threshing unit. It was found that seed moisture (MC), linear rotor speed (RS) and feed rate (FR) significantly influenced seed breakage, as shown in Table 7.

Table 7. Analysis of the variances of GB.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	4.49	3	1.50	259.66	< 0.0001*
A-MC	2.05	1	2.05	356.26	< 0.0001
B-FR	0.19	1	0.19	32.56	< 0.0001
C-RS	2.25	1	2.25	390.17	< 0.0001
Residual	0.075	13	5.767E-003		
Lack of Fit	0.055	11	4.997E-003	0.50	0.8185ns
Pure Error	0.020	2	1.000E-002		
Cor Total	4.57	16			

ns = Not significant, * = Significant at $p < 0.05$

From the lack-of-fit, it was found that the analytical equation had a p-value > 0.05. Therefore, a regression model that predicts the percent of seed breakage in an axial flow threshing unit can be expressed as Eq. (9).

$$GB = -1.018 + 0.110MC - 0.542FR + 0.188RS \quad (9)$$

Analysis of variance showed that the percent of grain breakage in an axial threshing unit followed a linear regression with a significantly low p-value (< 0.05), an adjusted R^2 of 0.9798 and a predicted R^2 of 0.9714, as shown in Table 8.

DOI:10.4186/ej.2024.28.4.51

Table 8. Model analysis affecting of GB

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2
Linear	< 0.0001	0.8185	0.9798	0.9714 [1]
2FI	0.8677	0.7399	0.9755	0.9547
Quadratic	0.5464	0.6975	0.9737	0.9337
Cubic	0.9149	0.2848	0.9522	0.0058 [2]

[1] = Suggested, [2] = Aliased

Equation (9) describes response surface methodology (RSM). The relationship between moisture content (MC), feed rate (FR), and linear rotor speed (RS) affected the percent of seed breakage during sunflower threshing can be seen in Fig. 9. When the feed rate (FR) was increased, the number of broken seed from sunflower threshing decreased. As the rotor speed (RS) increased, a higher percentage of seeds were broken. Due to the higher impact linear speed, the force applied to the sunflower disk is higher, causing more sunflower seeds to break during the threshing phase than at low impact speeds [21, 31, 37]. When the moisture content is decreased, the percentage of fractured seeds from kneading decreases. Moisture affects the capability of the seeds to remain attached to the flower disk and the hardness of the sunflower seeds [34–36]. This agrees with the results of Pachanawan, A. *et al.* [31].

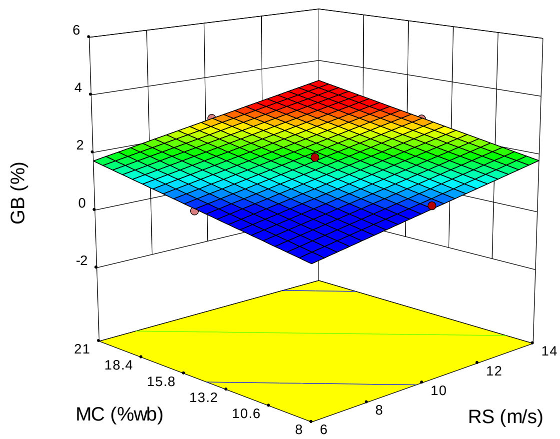

Fig. 9. Graphical response surface affecting GB.

3.2.4. Power requirements

Analysis of variance (ANOVA) for a linear regression in the design of a small axial flow sunflower threshing unit showed that the linear rotor speed (RS) and feed rate (FR) significantly influenced power requirements. Seed moisture (MC) did not significantly affect threshing losses, as shown in Table 9.

Table 9. Analysis of the variances of P

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	71942.24	3	23980.75	32.43	< 0.0001*
A-MC	780.30	1	780.30	1.06	0.3230
B-FR	5494.22	1	5494.22	7.43	0.0173
C-RS	65667.71	1	65667.71	88.82	< 0.0001
Residual	9611.65	13	739.36		
Lack of Fit	6978.98	10	634.45	0.48	0.8280ns
Pure Error	2632.68	3	1316.34		
Cor Total	81553.89	16			

ns = Not significant, * = Significant at $p < 0.05$

From the lack-of-fit, it was found that the analytical equation had a p-value > 0.05. A regression model that predicts the power required can be expressed as Eq. (10).

$$P = 445.03 + 2.149MC + 92.654FR + 32.032RS \quad (10)$$

The result of analysis of variance of the structural equation model and the statistical values affecting the power requirements found that a linear regression produced a relationship with a significantly low p-value (< 0.05), an adjusted R^2 of 0.8549 and a predicted R^2 of 0.7975, as shown in Table 10.

Table 10. Model analysis affecting of P.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2
Linear	< 0.0001	0.8280	0.8549	0.7975 [1]
2FI	0.9745	0.7308	0.8153	0.6098
Quadratic	0.8886	0.5965	0.7577	0.3102
Cubic	0.4540	0.5510	0.7844	-0.8182 [2]

[1] = Suggested, [2] = Aliased

While Eq. (10) describes the response surface methodology (RSM), the relationship between feed rate (FR), and linear rotor speed (RS) affected the power requirements for sunflower threshing, as can be seen in Fig. 10. The power required for threshing sunflower seeds increased with the feed rate (FR) and rotor speed (RS). Since the mass of sunflower seeds in the threshing chamber was directly proportional to the feed rate, it affected the force applied for threshing sunflower seeds [34, 25]. It was also found that higher kneading power was produced by greater rotor speeds [21, 31, 37]. This agrees with the results of Pachanawan, A. *et al.* [31].

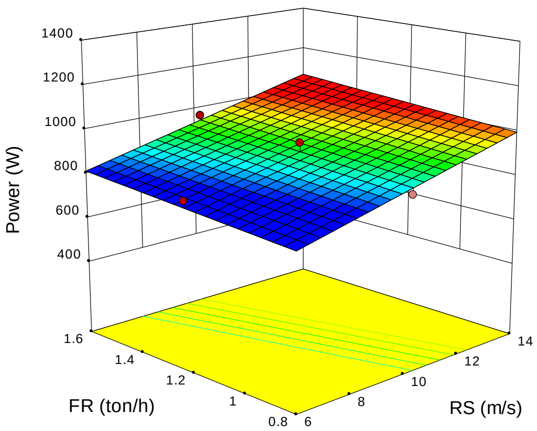

Fig. 10. Graphical response surface affecting power.

3.2.5. Specific energy consumption

Analysis of variance (ANOVA) for a linear regression in the design of a small axial flow sunflower threshing unit found that linear rotor speed (RS) and feed rate (FR) significantly influence specific energy consumption. The seed moisture (MC) did not significantly affect threshing losses, as shown in Table 11.

Table 11. Analysis of the variances of SEC.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	2.733E+005	3	91096	71.91	< 0.0001*
A-MC	619.15	1	619.15	0.49	0.4968
B-FR	2.254E+005	1	2.254E+005	177.89	< 0.0001
C-RS	47310.9	1	47311	37.35	< 0.0001
Residual	16469.1	13	1266.7		
Lack of Fit	14640.9	10	1331	1.46	0.4765ns
Pure Error	1828.25	3	914.12		
Cor Total	2.898E+005	16			

ns = Not significant, * = Significant at $p < 0.05$

From the lack-of-fit, the analytical equation had a p-value > 0.05. Therefore, a regression model that predicts the specific energy consumption can be expressed as Eq. (11).

$$SEC = 1187.46 + 1.91MC - 593.39FR + 27.19RS \quad (11)$$

The result of analysis of variance and the statistical values affecting the specific energy consumption indicated a linear regression with a significantly low p-value (< 0.05), an adjusted R^2 of 0.93 and a predicted R^2 of 0.8946, as shown in Table 12.

Table 12. Model analysis affecting of SEC.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2
Linear	< 0.0001	0.4765	0.9300	0.8946 [1]
2FI	0.8300	0.4024	0.9164	0.8668
Quadratic	0.0590	0.6309	0.9561	0.8789
Cubic	0.5526	0.4791	0.9538	0.4821 [2]

[1] = Suggested, [2] = Aliased

The relationship between feed rate (FR) and linear rotor speed (RS) affected the specific energy consumption of sunflower threshing, as shown in Fig. 11. When the feed rate (FR) was increased, the specific energy consumption for threshing sunflowers decreased [20, 39]. The feed rate was inversely proportional to the threshing-specific energy. Also, an increased threshing rotor speed (RS) increased specific energy consumption. The mass of sunflower seeds in the threshing chamber is directly proportional to the speed of the threshing ball. Therefore, the speed of the threshing ball affects the specific energy used in threshing the sunflower seeds to the same degree as the power used for threshing sunflower seeds [20, 34]. It was also found that higher kneading specific energy consumption was influenced by greater rotor speed [21, 31, 37], in agreement with Pachanawan, A. *et al.* [31].

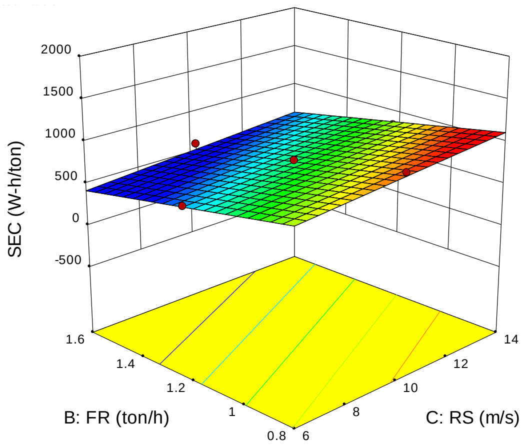

Fig. 11. Graphical response surface affecting SEC.

3.2.6. Grain purity

From analysis of variance (ANOVA) for a linear regression in the design of a small axial flow sunflower threshing unit, it was found that seed moisture (MC) and linear rotor speed (RS) significantly influence grain purity. The feed rate (FR) did not significantly affect grain purity. The grain purity percentage in threshing tended to increase with higher feed rates, as indicated in Table 13.

From the lack-of-fit, it was found that the analytical equation had a p-value > 0.05. A regression model that predicts grain purity is Eq. (12).

$$GP = 100.72 - 0.065MC + 0.206FR - 0.120RS \quad (12)$$

Analysis of variance and the statistical values affecting the grain purity showed a linear relationship with a significantly low p-value (< 0.05), an adjusted R^2 of 0.6833 and a predicted R^2 of 0.6168, as shown in Table 14.

Table 13. Analysis of the variance of GP.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	1.66	3	0.55	12.51	0.0004*
A-MC	0.71	1	0.71	15.93	0.0015
B-FR	0.027	1	0.027	0.61	0.4472
C-RS	0.93	1	0.93	20.97	0.0005
Residual	0.58	13	0.044		
Lack of Fit	0.44	10	0.040	0.60	0.7675 ns
Pure Error	0.13	3	0.067		
Cor Total	2.24	16			

ns = Not significant, * = Significant at p < 0.05

Table 14. Model analysis affecting SEC.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2
Linear	0.0004	0.7675	0.6833	0.6168 [1]
2FI	0.5318	0.7422	0.6663	0.6134
Quadratic	0.1055	0.9302	0.7909	0.6078
Cubic	0.8050	0.9768	0.6801	0.8692 [2]

[1] = Suggested, [2] = Aliased

The relationship between moisture content (MC) and linear rotor speed (RS) affected grain purity resulting from sunflower threshing, as indicated by Fig. 12. A lower moisture content of sunflower seeds resulted in higher cleanliness. The mass of broken seeds from threshing decreases, in agreement with Srison, W. *et al.* [19–20]. There is also evidence that increasing rotor speed (RS) will result in decreased seed cleanliness in sunflower threshing. This is because a higher rotor speed has a great effect on the percentage of fractured seeds. Therefore, seed cleanliness is reduced at low rotor speeds [20].

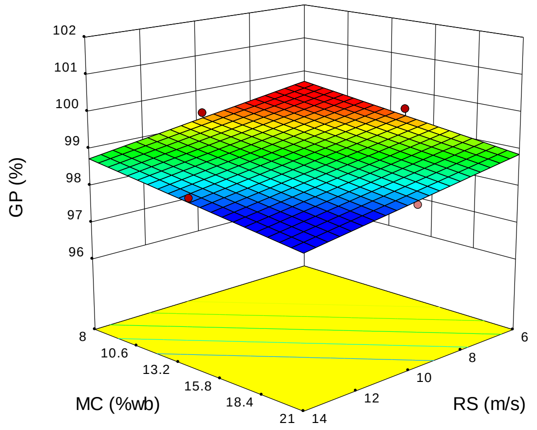

Fig. 12. Graphical response surface affecting GP.

4. Conclusions

The small axial flow sunflower threshing unit in the current study was extended from the earlier research of Pisal et al., who developed an axial flow sunflower threshing unit with dimensions of 1.90 m in length, 1.83 m in width, and 1.60 m in height, consisting of three main parts: 1) The spike tooth clearance is 125 mm. The length and diameter of the threshing rotor drum are 0.93 and 0.36 m, respectively. 2) The threshing sieve is made of round steel ribs with a concave rod clearance of 25 mm, and set the concave clearance to 10 mm, which is the suitable range for sunflower threshing [27]. and 3) The receptacle for the seeds in the threshing process that fall through the threshing sieve.

Evaluation of the performance of the developed threshing unit on the sunflower threshing performance can be summarized as follows.

Moisture content impacts the loses from sunflower threshing to a statistically significant degree. It was also found that if sunflowers have a low moisture content, grain breakage is decreased and sunflower threshing efficiency tends to be higher.

The feed rate effects for threshing power and the specific energy consumption were statistically significant. Lower feed rates tend to increase threshing efficiency. Conversely, higher feed rates result in higher grain purity.

The rotor speed effects on threshing efficiency, threshing loss, threshing percentage, threshing power, threshing specific energy, and grain purity were statistically significant. As rotor speed is increased, the percentage of broken seeds, threshing efficiency, threshing power, and threshing specific strength were greater, but threshing losses and grain purity were reduced.

The following are the ideal conditions for achieving maximum performance: 1. The moisture content of the sunflower threshing should be between 12 and 14 percent wet base. 2. The recommended feed rate is between 1,000 and 1,200 kg/h, and 3. The threshing rotor's linear speed should be between 10 and 12 m/s. With less than 2% threshing loss and grain breakage, the thresher unit will have a threshing efficiency greater than 98 percent [40, 41].

The present study focused on the design and operation of the axial flow sunflower massage unit, an integral component of the sunflower thresher. Future research should focus on exploring additional factors in the separation and cleaning of axial flow massage units.

References

[1] N. I. Nenko, N. N. Neshchadim, E. K. Yablonskay, and K. E. Sonin, "Prospects for sunflower cultivation in the Krasnodar Region with the use of plant growth regulator," *Helia*, vol. 39, no. 65, pp. 197-211, 2016.

[2] M. A. A. H. A. Bukhsh, J. Iqbal, S. Kaleem, A. Wasaya, and M. Ishaque, "Qualitative analysis of spring planted sunflower hybrids as influenced by varying nutritional area," *Pak. J. Nutr,* vol. 10, pp. 291–295, 2011.

[3] Y. Liu, C. Luo, W. Zong, X. Huang, L. Ma, and G. Lian, "Optimization of clamping and conveying device for sunflower oil combine harvester header," *Agriculture,* vol. 11, pp. 859, 2021.

[4] W. S. Cruvinel, K. A. D. P. Costa, A. G. Da Silva, E. D. C. Severiano, and M. G. Ribeiro, "Intercropping of sunflower with Brachiaria brizantha cultivars during two sowing seasons in the interim harvest," *Semin. Agrar*, vol. 38, pp. 3173–3191, 2017.

[5] R. K. Downey, G. Robbelen, and A. Ashri, *Oil Crop of the World, their Breeding and Utilization*. New York: McGraw Hill Publishing Company, 1989.

[6] M. Shahbandeh. "USDA-oilseeds world trade markets and trade-2022." US Department of Agriculture. Accessed: May 2022. [Online]. Available: https://www.statista.com/statistics/263928/production-of-sunflower-seed-since-2000-by-major-countries/

[7] Department of Agricultural Extension (DOAE). "Crop information, sunflower, Thailand." Accessed: May 2023. [Online]. Available: https://production.doae.go.th/service/report-product-statistic/

[8] A. Acampora, S. Croce, A. Assirelli, A. Del Giudice, R. Spinelli, A. Suardi, and L. Pari, "Product contamination and harvesting losses from mechanized recovery of olive tree pruning residues for energy use," *Renew Energy 2013*, vol. 53, pp. 350–353, 2013.

[9] R. Pecenka, H. Lenz, S. O. Jekayinfa, and T. Hoffmann, "Influence of tree species, harvesting method and storage on energy demand and wood chip quality when chipping poplar, willow and black locust," *Agriculture 2020*, vol.10, pp. 116, 2020.

[10] J. Schweier, B. Blagojević, R. Venanzi, F. Latterini, and R. Picchio, "Sustainability assessment of alternative strip clear cutting operations for wood chip production in renaturalization management of pine stands," *Energies*, vol. 12, no. 17, p. 3306, 2019.

[11] A. Bonfiglio and R. Esposti, "Analysing the economy-wide impact of the supply chains activated

by a new biomass power plant. The case of cardoon in Sardinia," *BAE*, vol. 5, no. 1, pp. 5–26, Jun. 2015.
[12] F. Cotana, G. Cavalaglio, V. Coccia, and A. Petrozzi, "Energy opportunities from lignocellulosic biomass for a biorefinery case study," *Energies*, vol. 9, no. 9, pp. 748, 2016.
[13] L. Špokas, D. Steponavičius, G. Žebrauskas, A. Čiplienė, and L. Bauša, "Reduction in adverse environmental impacts associated with the operation of combine harvesters during the harvesting of winter oilseed rape," *J. Environ. Eng. Landsc. Manag.* vol. 27, no. 2, pp.72–81, 2019.
[14] T. A. Haile, C. B. Holzapfel, and S. J. Shirtliffe, "Canola genotypes and harvest methods affect seedbank addition," *Agron. J.*, vol. 106, pp. 236–242, 2014.
[15] M. Fríd, A. Dolan, I. Celjak, M. Filip, and P. Bartos, "Harvest of cereals and oilseeds rape by combine harvesters New Holland CX 8090 and New Holland CR 9080," *Poljopr. Teh. 2017*, vol. 42, pp. 19–24., 2017.
[16] L. Špokas and D. Steponavičius, "Fuel consumption during cereal and rape harvesting and methods of its reduction," *J. Food, Agric. Environ.*, vol. 9, pp. 257–263, 2011.
[17] D. Kehayov, C. Vezirov, and A. Atanasov, "Some technical aspects of cut height in wheat harvest," *Agron. Res.*, vol. 2, pp. 181–186, 2004.
[18] L. Pari, F. Stefanoni, and W. Latterini, "Herbaceous oil crops, a review on mechanical harvesting state of the art," *Agriculture*, vol. 10, no. 8. pp. 309, 2020.
[19] W. Srison, S. Chuan-Udom, and K. Saengprachatanarug, "Design factors affecting losses and power consumption of an axial flow corn shelling unit," *Songklanakarin Journal of Science and Technology*, vol. 38, no. 5, pp. 591-598, 2016.
[20] W. Srison, S. Chuan-Udom, and K. Saengprachatanarug, "Effects of operation factors for an axial-flow corn shelling unit on losses and power consumption," *Agriculture and Natural Resources*, vol. 50, no. 5, pp. 421-425, 2016.
[21] S. Chuan-Udom, "Operating factors of Thai threshers affecting corn shelling losses," *Songklanakarin Journal of Science and Technology*, vol. 35, pp. 63-67, 2013.
[22] J. Fu, Z. Chen, L. Han, and L. Ren, "Review of grain threshing theory and technology," *International Journal of Agricultural and Biological Engineering*, vol. 11, no. 3, pp. 12-20, 2018.
[23] J. O. Olaoye, K. C. Oni, and M. O. Olaoye, "Computer applications for selecting operating parameters in a stationary grain crop thresher," *Journal of Agricultural Technology*, vol. 7, no. 1, pp. 39-56, 2011.
[24] M. M. Konstantinov and I. N. Glushkov "Assessment of grain loss rate in the process of harvesting with a windrow reaper equipped with a device for stubble coulisses forming," *Bulletin of Agrarian Science*, *The Theoretical and Scientific Journal*, vol. 3, no. 59, pp. 86-89, 2016.
[25] P. Saeng-ong, S. Chuan-Udom, and K. Saengprachatanarug, "Effects of guide vane inclination in axial shelling unit on corn shelling performance," *Kasetsart Journal (Natural Science)*, vol. 49, no. 5, pp. 761-771, 2015.
[26] S. Chuan-Udom, P. Thongsawatwong, K. Saengprachatanarug, and E. Taira, "Peg-tooth spacing and guide vane inclination of a Thai combine harvester affecting harvesting losses," *Engineering and Applied Science Research*, vol. 45, no. 2, pp. 107-111, 2018.
[27] P. Muenkaew, J. Duangkhamjan, and S. Chuan-Udom, "Factors affecting sunflower threshing performance of a small axial flow threshing unit," *Engineering and Applied Science Research*, vol. 49, no. 5, pp. 720-3, 2022.
[28] W. Chansrakoo and S. Chuan-Udom, "Factors of operation affecting performance of a short axial-flow soybean threshing unit," *Eng. J.*, vol. 22, no. 4, pp. 109-120, 2018.
[29] A. U. Khan, "The Asian axial-flow thresher," in *Small Farm Equipment for Developing Countries.* USA: McGraw-Hill Book Company, 1986, pp. 373-387.
[30] B. Lenaerts, T. Aertsen, E. Tijskens, B. D. Ketelaere, H. Ramon, and J. D. Baeraemaeker, "Simulation of grain–straw separation by discrete element modeling with bendable straw particles," *Computers and Electronics in Agriculture*, vol. 101, pp. 24–33, 2014.
[31] A. Pachanawan, K. Doungpueng, and S. Chuan Udom, "Effects of disc peg drum parameters on maize shelling performance of an axial flow shelling unit," *International Journal of Agricultural Technology*, vol. 17, no. 1, pp. 257-276, 2021.
[32] P. D. Berger and R. E. Maurer, *Experimental Design with Applications in Management, Engineering, and the Sciences*. California: Duxbury Thomson Learning, 2002.
[33] United Nations, *RNAM Test Codes & Procedures for Farm Machinery, Technical Series No. 12*, 2nd ed. Bangkok, Thailand: Economic and Social Commission for Asia and the Pacific, Regional Network for Agricultural Machinery, 1995.
[34] S. K. A. Al Sharifi, M. A. Aljibouri, and M. A. Taher, "Effect of threshing machines, rotational speed and grain moisture on corn shelling," *Bulgarian Journal of Agricultural Science*, vol. 25, no. 2, 2019.
[35] D. Steponavičius, E. Pužauskas, L. Špokas, E. Jotautienė, A. Kemzūraitė, and S. Petkevičius, "Concave design for high-moisture corn ear threshing," *Mechanics*, vol. 24, no. 1, pp. 80-91, 2018.
[36] P. Wacker, "Maize grain damage during harvest," *Landtechnik,* vol. 60, no. 2, pp. 84-85, 2005.
[37] Y. Yu, H. Fu, and J. Yu, "DEM-based simulation of the corn threshing process," *Advanced Powder Technology*, vol. 26, no. 5, pp. 1400-1409, 2015.

[38] A. C. Ukatu, "A modified threshing unit for soya beans," *Biosystems Engineering,* vol. 95, no. 3, pp. 371-377, 2006.

[39] N. El-Desukey, E. Mousa, and A. Lotfy, "Feasibility of using corn sheller machine in threshing sunflower," *J. Agric. & Env. Sci. Alex .Univ., Egypt*, vol. 6, no. 3, pp. 17-33, 2007.

[40] F. Cotana, G. Cavalaglio, V. Coccia, and A. Petrozzi, "Energy opportunities from lignocellulosic biomass for a biorefinery case study," *Energies*, vol. 9, pp. 748, 2016.

[41] S. Petkevicius, L. Spokas, and D. Steponavicius, "Sub-stantiation of technological parameters of wet maize ear threshing," *Agronomy Research*, vol. 6, no. Special issue, pp. 271-280, 2008.

Pisal Muenkaew, photograph and biography not available at the time of publication.

Somchai Chuan-Udom, photograph and biography not available at the time of publication.

Anuwat Pachanawan, photograph and biography not available at the time of publication.