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Designing a waxy maize shredder for animal feed

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Abstract The results showed that the knife sharpening angle and blade speed significantly affected the waxy maize shredder capacity, shredder loss and shredder efficiency ($P < 0.05$). The 30° knife sharpening angle and 1100 rpm blade speed resulted to high shred capacity, efficiency and low shred loss, hence these were selected as the optimal factors for developing the shredder. The size of the stalks was 2.57±1.25 cm, which is suitable size for animal feed. The engineering economic cost analysis showed that the average working cost was 0.35 baht/kg, the break-even point was 190 hours/year, and when considering the 600 hours/year of work, the payback period was 1.4 years.

Keywords: Physical properties, Maize stalk, Maize shredder, Knife sharpening angle

Introduction

Maize (*Zea mays* L.) holds significant economic importance in Thailand, making it one of the country's key crops. In fact, Thailand stands as the world's second-largest producer of maize, surpassed only by Nigeria (FAO, 2023; Office of Agricultural Economics, 2023). The country possesses approximately 234,402 rai (37,504.32 ha) of arable land, predominantly located in the northern, central, and northeastern regions. This abundance of arable land contributes substantially to the country's income.

In Thailand, maize cultivation can be categorized into two main groups: specialty maize and maize grown for food consumption and export due to its high nutritional value. Furthermore, the stalks are utilized for animal feed production (Lomchangkum *et al.,* 2022). Dairy farmers currently face challenges associated

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with the escalating costs of milk production, particularly animal feed expenses. Hence, it becomes crucial to explore approaches that can alleviate costs for farmers. One potential strategy involves utilizing roughage due to its advantageous properties and cost-effectiveness.

According to statistics from Thailand, there were 17,348 households (representing 584,327 cows) engaged in dairy farming in 2022. Roughage and concentrates play a pivotal role in animal feed composition. The primary components of animal feed encompass concentrated food, minerals, vitamins, and roughage, such as fresh grass, silage, or hay. A report from the Department of Livestock Development in Thailand indicated that cows and buffaloes consume approximately 7 kg/head of dry food, resulting in a demand for approximately 60,000 tons/day or 21.9 million tons/year of hay (Department of Livestock Development, 2023). In light of this significant demand and associated costs, dairy farmers are actively seeking alternative plants to feed their dairy cows. However, the adoption of alternative plants has led to slower growth of dairy cows, consequently reducing the income of many farmers who lack sufficient grazing land.

Maize stalks have emerged as a potential alternative crop for use as roughage due to their advantageous feed quality and suitability for silage production. Furthermore, maize stalks can be used as animal feed during the dry season when there is a scarcity of fresh grass. The research aimed to develop an efficient waxy maize shredder specifically designed for animal feed.

Materials and methods

A maize shredder for animal feed was developed in Thailand. The research methodology involved a systematic approach, which encompassed gathering and analyzing the essential data for the design phase. Subsequently, a maize shredder was constructed based on the gathered information. Finally, the performance of the maize shredder was thoroughly tested and evaluated.

Study of the physical properties of maize stalks

The specific investigation was assessed the physical characteristics of maize stalks, including measurements of stalk height, stalk diameter, total weight of the stalk, moisture content, stalk density, and coefficient of friction. It was established a basis for the design of a maize shredder. To ensure the reliability and validity of our findings, it focused on examining the widely cultivated waxy maize variety Neaw Maung Tam, which is commonly grown in Thailand.

A sample was collected the dataset consisting of one hundred maize stalks harvested after 70 days. The assessment methodology was employed by strictly adhered to the guidelines established by Mohsenin (1986). These guidelines provided a comprehensive framework, and enabled to accurately measured and evaluated the relevant physical properties of the maize stalks (Figure 1).

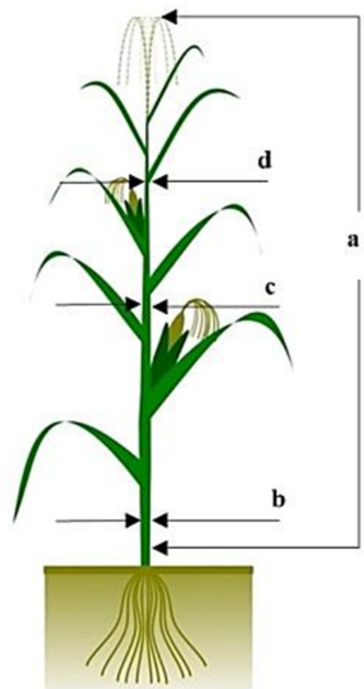


Figure 1. Measurements of physical properties of Maize stalk (a - total height, b - bottom diameter, c - middle diameter, and d - top diameter)

Design and construction of a maize shredder for animal feed

To enable and guarantee the efficacy of the maize shredder, it was imperative to obtain the essential data regarding its design and experimentation stages. Therefore, the design process was divided into two key phases: firstly, outlining the design criteria, and secondly, scrutinizing the fundamental components of the shredder. The following sections explicated the specific of the design and construction process.

Design and construction criteria for an efficient maize shredder for animal feed

The ideal maize shredder should possess several key characteristics to meet the needs of farmers during the post-harvest phase. Firstly, it should be of medium size, providing portability and convenience for farmers as they shred maize stalks. Secondly, the shredder must have the capability for continuous shredding to enhance overall efficiency. Additionally, its working mechanism should be designed with simplicity in mind, allowing farmers to perform repairs without the need for external assistance. Emphasis should also be placed on low maintenance requirements, ensuring that damaged parts can be readily replaced. Moreover, the shredder should incorporate a small engine with a power output of 5 hp. Lastly, it should be easily operable by a single operator, promoting optimal usability and cost-effectiveness for farmers.

Designing the key components of a maize shredder: results and insights

The development of the maize shredder was carried out through the application of well-established Engineering Design Principles (Shigley and Mischke, 1989) in addition to Agricultural Machinery Design Principles (Krutz *et al*., 1994). The prototype consisted of four essential components, including the main structure, feed chute, shredder blade set, and transmission system, which employed a small engine as its power source (Figure 2). Further insights into the design specifics are expounded below.

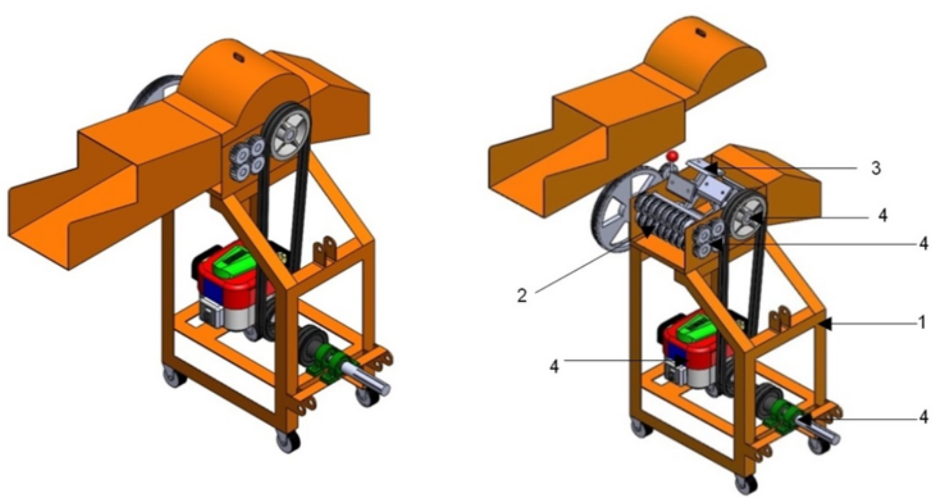


Figure 2. The prototype of maize shredder for animal feed

The primary framework of the shredder was constructed by welding together a 2-inch angle steel with a thickness of 3 mm. The dimensions of the shredder structure were 40 mm in width, 742 mm in length, and 550 mm in height, with an upward connection. This framework served as the mounting kit for the maize stalk shredder and powertrain components, as depicted in Figure 3.

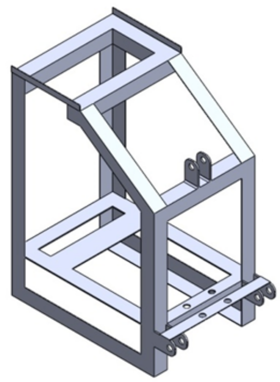
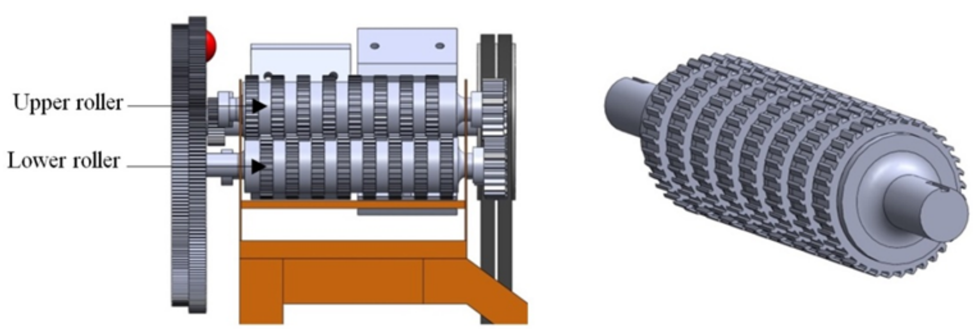


Figure 3. The main structure of prototype

The feeding chute was composed of two separate sets of upper and lower rollers, which were crafted to rotate in opposite directions. These rollers were highly effective in drawing the maize stalks into the shredder. Each individual set of rollers was intricately linked to eight gears, with each gear featuring a 30° angle per gear tooth. The dimensions of each roller set were precisely measured to be 62 mm in diameter and 250 mm in length. The specific intent behind this design was to ensure a secure grasp and to prevent any slippage while shredding the maize stalks, as can be observed in Figure 4.



(a) The position of the upper and lower rollers.

(b) The roller type gear.

Figure 4. The feeding chutes

The shredder employed a series of blades comprising of an eight-blade configuration with high speed. Each blade had a width of 75 mm, a length of 115 mm, and a thickness of 3 mm. These blades were meticulously fastened to the cylindrical head of the shredder frame and were strategically located at the forefront of the maize stalks, as shown in Figure 5.

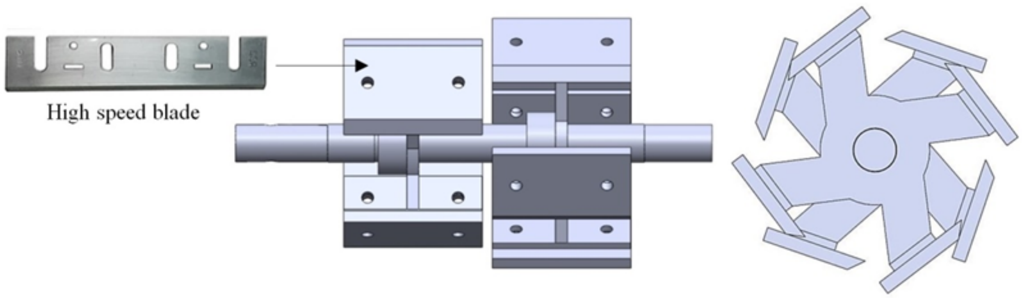


Figure 5. The shredder blade set

The prototype's transmission system incorporated three power supply connections for enhanced functionality in agricultural fields, as illustrated in Figure 6. These connections included: 1) a small engine connection, 2) a walking tractor connection, and 3) a tractor connection. This arrangement ensured convenient operation, especially in areas where the maize shredder would not be easily accessible. The transmission system operated based on a simple yet effective principle. Initially, power was transmitted from the small engine to the drive and return pulleys using a belt mechanism. Subsequently, the power was further transferred to the gears of each roller, as depicted in Figure 7.

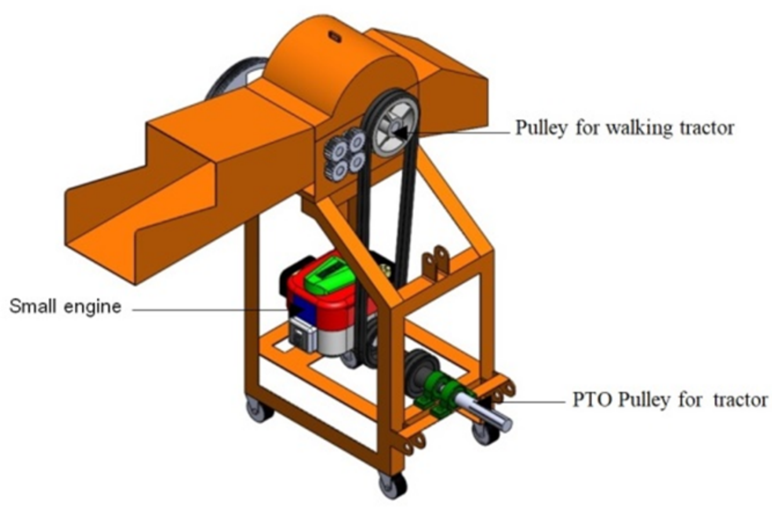


Figure 6. Connection points for the power

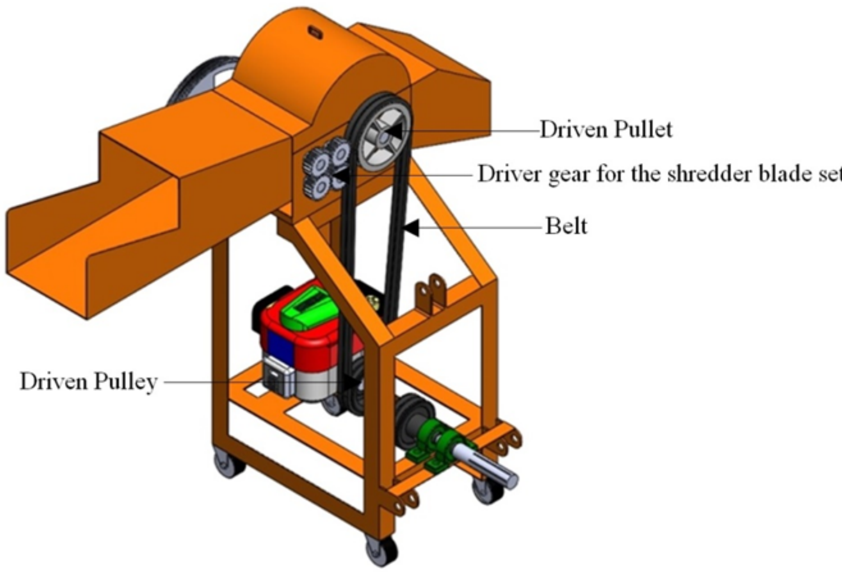


Figure 7. Components of the transmission system

Testing and evaluation of the operation of the maize stalk shredder for animal feed

Materials and equipment

In this study, various materials and equipment were employed to facilitate the research processes effectively. These included a prototype maize shredder, a specially designed machine tailored for the purpose of efficiently shredding maize stalks. Additionally, a stopwatch was utilized to precisely measure time intervals, ensuring accuracy in data collection. Furthermore, a tachometer, an instrument specifically designed for measuring the rotational speed of the blade, played a pivotal role in the study. Lastly, digital weighting scales, known for their precision, were used to accurately measure the weight of the samples, contributing to the overall reliability and rigor of the research.

Factors studied

In this study, an investigation was carried out on several factors. The sharpness of the blade was assessed at three distinct angles, specifically 15°, 30°, and 45°, as illustrated in Figure 8. These angle values were adopted with reference to the research conducted by Persson (1987). Additionally, the speed of the blade was examined at three varying levels, which corresponded to blade speeds of 900, 1100, and 1300 rpm, equating to linear velocities of 62.83, 69.11, and 73.23 m/s, respectively. The basis for selecting these blade speed levels was drawn from the work conducted by Chattopadhyay and Pandey (1998).

(a) 15° (b) 30° (c) 45°

Figure 8. The characteristics of knife sharpening angle in the study

Test methods

The experiment commenced by measuring the weight of maize stalks. The shredder blade test was conducted using a sharp angle of 15°, a speed of 900 rpm, and a feed rate of 2 kg/hr. The maize stalks were then fed into the shredder where the roller pulled them in. The time taken from the beginning until all the stalks were shredded was recorded. After shredding, the shredded stalks, fallen stalks, and unshredded stalks were weighed. The experiment was replicated three times (Figure 9). The collected data was utilized in subsequent calculations, specifically employing equations 1-3. To maintain consistency, the test factors were altered and calculations were performed following the method described by Kalasirisilp *et al.* (2019).

(a) Testing the sharpness of the blade (b) Testing the speed of the blade

Figure 9. The testing of the relationship between the knife sharpening angle and the blade speed

Indicators

Shredder capacity. (Langkapin *et al.,* 2012).

$$C_p = \frac{m_1}{t} \tag{1}$$

Where; C_p = Shredder capacity (kg/hr)
m_1 = Weight of all chopped maize stalks (kg)
t = Total operation time (hr)

Shredder loss. (Lomchangkum *et al.,* 2020)

$$L_s = \frac{m_2}{m_1 + m_2} \times 100 \tag{2}$$

Where; L_s = Amount of loss after maize chopping (%)
m_1 = Weight of all chopped maize stalks (kg)
m_2 = Total weight of maize stalk loss (the weight of fallen and unshredded stalks) (kg)

Shredder efficiency

$$\eta = \frac{m_1}{m_2} \times 100 \tag{3}$$

Where; η = work efficiency (%)
m_1 = Weight of shredded maize stalks (kg)
m_2 = Total weight of maize stalk loss (the weight of fallen and unshredded stalks) (kg)

Data analysis

Statistical principles of Analysis of Variance (ANOVA) were analyzed. Duncan's multiple range test was compared for mean comparison at a confidence level of 95%. This was done to assess the relationship between knife sharpening angle and blade speed.

Engineering economic cost analysis

Break-even point

The break-even point refers to the annual operational time calculation for a machine which compares the costs associated with laborers and a prototype shredder, while considering that the cost of employing human labor is equal to the cost of using the maize shredder. Equation 4 (Hunt, 2001) is used to calculate this.

$$BEP = \left[\frac{F_c}{B - VC} \right] \quad (4)$$

Where;BEP = Break-even point (hr/year)
Fc = Fixed expenses (Baht)
B = Hire rate (Baht/hr)
VC = variable cost (Baht/hr)

Payback period analysis

The payback period calculation is used to determine the number of years required to return the initial investment in the maize stalk shredder. This computation, illustrated in equation 5 (Hunt, 2001), provides valuable insight into the time frame during which the returns on the investment are expected to be realized.

$$PBP = \left[\frac{P}{R} \right] \quad (5)$$

Where; PBP = Payback period (years)
P = Machine Price (Baht)
R = Annual net profit (Baht/year)

Results

The physical properties of maize stalks

The results pertaining to the physical attributes of 100 waxy maize stalks, which were assessed 70 days after the harvest as seen in Table1. The heights of the stalks exhibited a range spanning from 145.5 cm to 197.4 cm, with an average height of 168.5 cm and a standard deviation (SD) of 2.0. Similarly, the bottom diameters varied from 1.4 cm to 2.1 cm, with an average value of 1.7 cm and an associated standard deviation (SD) of 1.5. The middle diameters ranged from 1.0 cm to 1.6 cm, yielding an average value of 1.3 cm and a standard deviation (SD) of 0.8. Additionally, the top diameters were observed to fall between 0.6 cm and 1.1 cm, resulting in an average value of 0.9 cm, accompanied by a standard deviation (SD) of 2.0. In terms of weight, the stalks exhibited weights spanning from 59.8 g to 298.1 g, with an average weight of 156.1 g and a standard deviation (SD) of 2.9. The moisture content averaged the value of

70.1% (w.b.), and the average stalk density was established at 0.24 g/cm^3. Furthermore, an average coefficient of static friction angle of 28° was recorded. These findings were subsequently employed as crucial inputs in the design of the maize shredder. For instance, the stalk height informed the design of the feeder chute, the stalk diameter influenced the configuration of the feed roller, and due consideration was given to the coefficient of static friction angle when designing the output chute post-shredding.

Table 1. Physical properties of purple glutinous rice cultivars (waxy maize) stalks

Properties	Height (cm)	Diameter (cm)			Total weight (g)
	(a)	Bottom (b)	Middle (c)	Top (d)	
Max.	197.4	2.1	1.6	1.1	298.1
Min.	145.5	1.4	1.0	0.6	59.8
Avg.	168.5	1.7	1.3	0.9	156.1
S.D(±)	2.0	1.5	0.8	2.0	2.9

Average data with ± a standard deviation.

The results of the design and construction of a waxy maize shredder for animal feed

The components of the maize shredder, which encompass the following elements: the shredder structure, feeding chute, chopper blade set, and transmission system is presented in Table 2. The dimensions of the maize shredder for animal feed are 40 mm in width, 742 mm in length, and 550 mm in height. The roller measures 62 mm in diameter and 250 mm in length, while the chopper blade set has a diameter of 157 mm and consists of eight blades. The feeder chute's dimensions are 157 mm in width and 1500 mm in length. The power of the machine is 5 hp.

Table 2. Details of the components of the maize shredder for animal feed

Description	Specification
Dimension of maize shredder size	40 mm x 742 mm x 550 mm (width x length x height)
Diameter and length of roller	62 mm in diameter, 250 mm in length
Diameter of chopper blade set	157 mm. in diameter, 8 blades
Size of feeder chute	157 mm x 1500 mm (width x length x height)
Power machine	5 hp

The operation of the maize shredder involved the initial step of feeding maize stalks into the feeder chute. The upper and lower rollers, rotating in opposite directions, effectively pulled the stalks into the shredding chamber.

Within the chamber, a set of 8 blades skillfully shredded the stalks into smaller pieces. These shredded pieces were collected in a tightly tied plastic bag to keep water and air out. Subsequently, the collected stalk pieces underwent a fermentation process lasting 3-4 weeks, transforming them into silage stalks suitable for animal feed. Alternatively, the shredded stalk pieces could be directly fed to animals without undergoing fermentation. For a comprehensive understanding of the maize shredder's key components, as refered to Figure 10.

Figure 10. Components of the prototype of maize shredder

The evaluation of the operation of the maize shredder for animal feed

In order to assess the performance of the prototype maize shredder, various factors were considered. The variables were encompassed knife sharpening angle at inclinations of 15°, 30°, and 45°, blade velocity ranging from 900 to 1300 rpm, and a feed rate equivalent to 2 kg/hr. Each test utilized a sample consisting of 2 kg of waxy maize stalks, and three replications were conducted to ensure accuracy and reliability.

Shredder capacity

The findings demonstrated a significant impact of knife sharpening angle and blade speed on shredder capacity ($P < 0.05$). Increasing both factors positively influenced the shredder capacity. Among the various knife sharpening angle levels, the 30° setting consistently exhibited the highest shredder capacity across all blade speed levels (Figure 11). Therefore, it was selected for further analysis. When the results were compared, the combination of 30° knife sharpening angle and 1100 rpm blade speed yielded the highest shredder capacity at 315.45±3.67 kg/hr, with an optimal stalk size of 2.57±1.25 cm (Figure 12). For more detailed information as seen in Table 3.

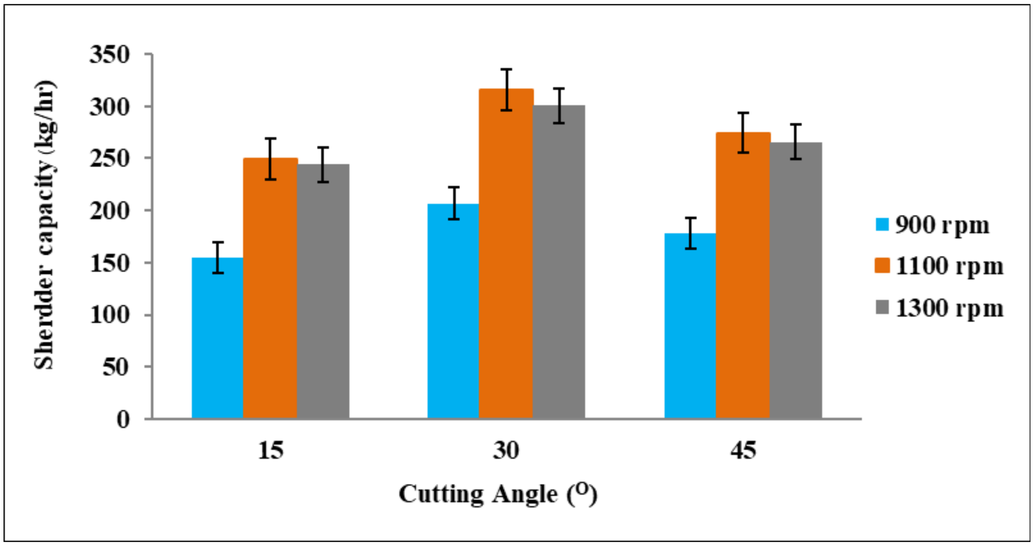


Figure 11. The relationship between knife sharpening angle and shredder capacity

(a) (b) (c)

Figure 12. (a) The stalk shredded with a 15° knife sharpening angle. (b) The stalk shredded with a 30° knife sharpening angle. (c) The stalk shredded with a 45° knife sharpening angle

Shredder loss

The study findings revealed that both knife sharpening angle and blade speed had a significant impact on shredder loss ($P < 0.05$). Increasing knife sharpening angle and blade speed decreased in shredder loss. Among the different knife sharpening angles tested, the 30° setting consistently exhibited the lowest shredder loss across all levels of blade speed (Figure 13), making it the preferred choice for further analysis. Comparison of results indicated that the combination of a 30° knife sharpening angle and a blade speed of 1000 rpm resulted in the lowest shredder loss (25.45±1.78%), as shown in Table 3.

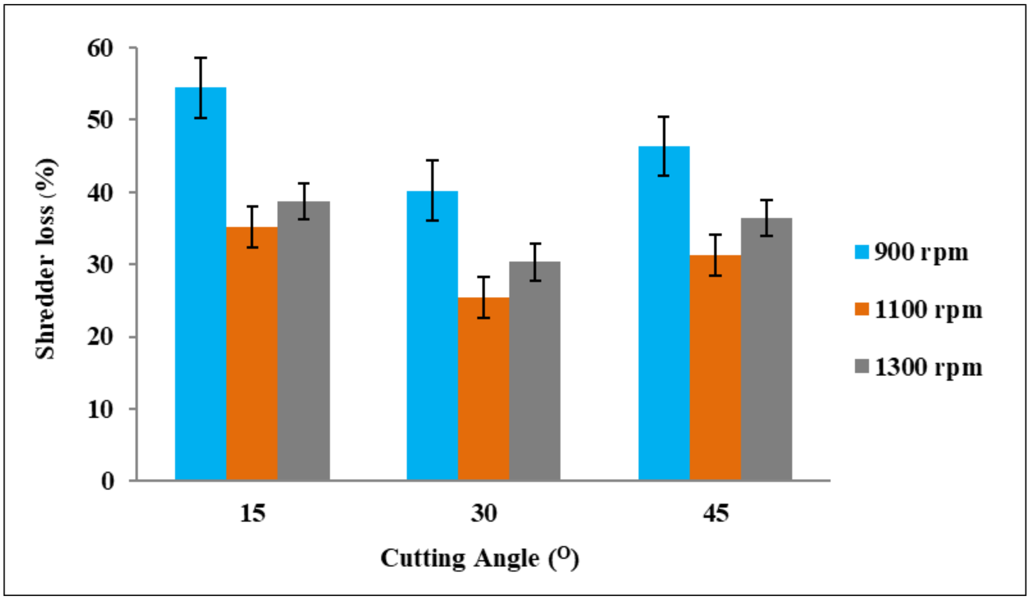


Figure 13. The relationship between knife sharpening angle and shredder loss

Shredder efficiency

The findings of the study demonstrated that both knife sharpening angle and blade speed had a significant impact on shredder efficiency ($P < 0.05$). Increasing the knife sharpening angle and blade speed resulted in higher shredder efficiency. Among the knife sharpening angles tested, the 30° setting consistently exhibited the highest shredder efficiency across all levels of blade speed (Figure 14), warranting its selection for further analysis. Comparative analysis revealed that the combination of a 30° knife sharpening angle and a blade speed of 1100 rpm resulted in the highest shredder loss (65.28±2.13%), as shown in Table 3. Knife sharpening angles less than 30° and blade speeds below 1100 rpm caused excessive stalk length and breakage, rendering the resulting stalk size unsuitable for animal feed. Conversely, when the knife sharpening angle exceeded 30° and the blade speed dropped below 1100 rpm, the blade failed to make sufficient contact with the stalks, leading to overly long sized stalks. Additionally, during shredding, some stalks fell due to the high blade speed, resulting to increase shredder loss.

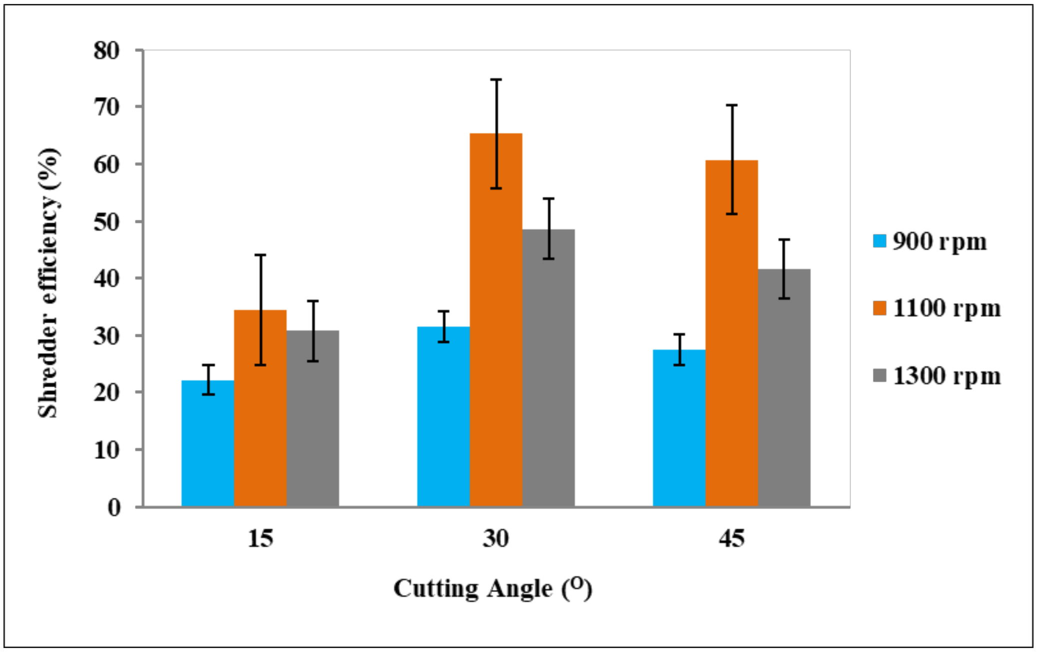


Figure 14. The relationship between knife sharpening angle and shredder efficiency

Table 3. Average results of the test and evaluation of the maize shredder machine for animal feed

Knife sharpening angle (°)	Blade speed (rpm)	Stalk size (cm)	Shredder capacity (kg/hr)	Shredder Loss (%)	Shredder efficiency (%)
	900	$5.60^{c}\pm3.50$	$154.45^{c}\pm0.31$	$54.45^{c}\pm0.45$	$22.23^{c}\pm1.45$
15	1100	$6.18^{b}\pm2.11$	$248.86^{b}\pm4.14$	$35.12^{b}\pm0.12$	$34.43^{b}\pm0.89$
	1300	$7.34^{a}\pm1.11$	$243.67^{a}\pm2.08$	$38.67^{a}\pm2.32$	$30.77^{a}\pm1.32$
	900	$4.19^{c}\pm2.30$	$206.56^{c}\pm1.34$	$40.23^{c}\pm1.25$	$31.45^{c}\pm2.45$
30	1100	$2.57^{b}\pm1.25$	$315.45^{b}\pm3.67$	$25.45^{b}\pm1.78$	$65.28^{b}\pm2.13$
	1300	$5.64^{a}\pm2.35$	$300.23^{a}\pm1.44$	$30.30^{a}\pm1.27$	$43.34^{a}\pm2.00$
	900	$2.40^{c}\pm3.20$	$178.12^{c}\pm2.34$	$46.36^{c}\pm2.32$	$27.56^{c}\pm0.56$
45	1100	$1.55^{b}\pm2.55$	$274.13^{b}\pm1.22$	$31.26^{b}\pm1.23$	$60.78^{b}\pm2.34$
	1300	$3.45^{a}\pm1.21$	$265.55^{a}\pm3.25$	$36.34^{a}\pm2.56$	$41.67^{a}\pm1.48$

Means in the same column followed by the same superscript are not statistically different at ($P < 0.05$), Average data with ± is a standard deviation

Engineering economic cost analysis

The economic analysis of this study considered the following conditions: one operator, fuel consumption rate of 1.5 liters per hour, shredder capacity of 315.45 kg/hr, and a construction cost of 25,000 THB for the maize shredder. The findings revealed that the break-even point was reached at 190 hours per year, with the maize shredder operating for 600 hours per year. The cost associated with utilizing the maize shredder was established at 0.35 THB per kilogram, while the period required to recoup the investment was computed as 1.4 years.

Discussion

In pursuit of optimizing animal feed production from waxy maize, this study sought to design a customized shredder tailored to this purpose. Analysis of the physical properties of maize stalks from the waxy maize cultivar unveiled measurements averaging 168.5 cm in height, 1.7 cm in bottom diameter, 1.3 cm in middle diameter, 0.9 cm in top diameter, and 156.1 g in weight. Moisture content averaged 70.1% (w.b.), stalk density stood at 0.24 g/cm^3, and the coefficient of static friction angle measured 28°. Based on these insights, a meticulously engineered prototype shredder was constructed, comprising a main structure, feed chute, shredder blade set, and a transmission system powered by a compact engine.

Performance assessments were undertaken, considering varying knife sharpening angles of 15°, 30°, and 45°, blade speeds of 900, 1100, and 1300 rpm, and a feed rate of 2 kg/hr, with three replications using 2 kg samples of maize stalks. The study found that both knife sharpening angle and blade speed significantly influenced the shredder's capacity. Specifically, increasing the knife sharpening angle and blade speed positively impacted the shredder's capacity, with the optimal combination being a 30° knife sharpening angle and 1100 rpm blade speed, yielding the highest capacity. These results are in line with Langkapin *et al*. (2012) prior research on cassava root picking machinery.

The investigation also revealed the impact of knife sharpening angle and speed on shredder losses. Elevating both parameters led to reduced shredder losses, with the lowest loss observed at a 30° knife sharpening angle and 1000 rpm blade speed. Notably, knife sharpening angles below 30° and blade speeds exceeding 1100 rpm caused stalk elongation and breakage, rendering the resulting stalk size unsuitable for animal feed. Conversely, angles greater than 30° and speeds below 1100 rpm resulted in insufficient cutting, producing overly long stalks. These findings align with Ghahraei *et al*. (2008) work on sweet sorghum cutting systems and Pachanawan *et al*. (2021) study on maize shelling efficiency.

Furthermore, the study assessed shredder efficiency concerning knife sharpening angle and speed. Increasing both parameters led to higher shredder efficiency, with the optimal combination being a 30° knife sharpening angle and 1100 rpm blade speed. Similar to the loss aspect, angles less than 30° and speeds below 1100 rpm resulted in excessive stalk length and breakage, while angles exceeding 30° and speeds below 1100 rpm failed to adequately engage with the stalks. These results corroborate Ghahraei *et al*. (2008) findings regarding sweet sorghum cutting profiles and Pachanawan *et al.* (2021) observations on maize shelling efficiency.

Economically, the study considered key parameters including one operator, a fuel consumption rate of 1.5 liters per hour, a shredder capacity of 315.45 kg/hr, and a construction cost of 25,000 THB for the maize shredder. The analysis revealed a break-even point at 190 hours per year, with the maize shredder operating for 600 hours per year. The cost per kilogram associated with using the maize shredder was calculated at 0.35 THB, and the investment payback period was determined to be 1.4 years.

In conclusion, the introduction of this prototype shredder presented a promising opportunity to enhance farmers' productivity, reduce operational costs, and increase income generation. Additionally, it is contributed to advancements in agricultural machinery for crop shredding, fostering progress in the field of agriculture.

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