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Innovative design and development of a compact maize shelling machine

Srila, M.[1], Doungpueng, K.[2], Rayanasuk, K.[3] and Pachanawan, A.[3*]

[1]Department of Manufacturing Industry Technology, Fuculty of Engineering, Maha Sarakham Rajabhat University, Maha Sarakham, Thailand; [2]Department of Farm Mechanics, Faculty of Technical Education, Rajamangala University of Technology Isan Khon Kaen Campus, Khon Kaen, Thailand; [3]Division of Agricultural Engineering and Technology, Faculty of Agricultural and Natural Resources, Rajamangala University of Technology Tawan-ok, Chonburi, Thailand.

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Abstract A maize sheller tailored for efficiently separating maize grains from the cob was designed. Selecting an appropriate maize sheller is essential for improving work efficiency and minimizing maize shelling losses. The developed maize sheller is characterized by its lightweight, cost-effectiveness, simple operation, and easy maintenance, ultimately saving valuable work time. The roller sheller, a key component in this study, has dimensions of 300 mm in length and a 50 mm diameter. The design process included performance testing and an economic analysis. The study explored three sheller speeds (450, 650, and 850 rpm) and four sheller screen levels (10, 12, 14, and 16 mm). Results indicated a shelling efficiency (SE) of 82.1%, with grains breakage at 10.82%. The break-even point for using the roller maize sheller is determined to be 6,878 kg/year. Assuming a labor wage rate was 1 baht/kg, a machine price set was 24,000 baht, and a payback period is for 0.18 years (equivalent to 2 months).

Keywords: Maize, Shelling Machine, Shelling roller, Selling efficiency, Break-even point

Introduction

Maize cultivation holds immense significance within the world's animal feed industry (Oladejo *et al.,* 2011; Farjam *et al.,* 2014) and serves as a crucial economic crop in Thailand. Beyond its primary role in animal feed production, maize presents avenues for value addition through the creation of derivatives such as starch, oil, glue, ethanol, and industrial alcohol (Haros *et al.,* 2003; Naqvi *et al.,* 2011; Wallington *et al.,* 2012; Ranum *et al.,* 2014). In Thailand, the cultivation of maize predominantly takes place during the dry season, following rice harvests, in areas equipped with sufficient water sources or irrigation systems. Notably, maize cultivation has a water efficiency advantage over rice,

[*] **Corresponding Author**: Pachanawan, A.; **Email**: anuwat_pa@rmutto.ac.th

requiring 2-3 times less water than rice farming, thereby contributing to the income generation of local farmers. Nonetheless, maize yields frequently grapple with challenges related to elevated humidity levels, which can compromise product quality. Consequently, meticulous management of maize seed quality, particularly during critical phases like harvesting and shelling, remains imperative (Bakoye *et al.,* 2017; Fox and O'Hare, 2017).

Currently, endeavors are underway to develop compact axial flow maize shelling solutions, limited to a maximum length of 900 mm, suitable for utilization with tractors and adaptable to steep terrains (Srison *et al.,* 2016; Pachanawan *et al.,* 2021). Despite modifications aimed at accommodating high-powered agricultural machinery, the dependence on the primary power source for shelling still presents challenges, necessitating manual separation of seeds from cobs, a process that can be time-consuming.

A study conducted by Tunhaw *et al.* (2020) on maize sheller double crackers, incorporating a 10 cm diameter rasp bar sheller, revealed that optimal maize shelling efficiency was achieved at a linear speed of 12 m/s with moisture content not exceeding 11.57 %wb. These findings aligned with favorable performance metrics for a sheller measuring 120x100x80 cm. Moreover, Uttam *et al.* (2018) reported a maize shelling efficiency of 95.89% at a moisture content of 13%wb and a sheller speed of 889 rpm.

In the field of maize shelling machines, Aremu *et al.* (2015) documented an efficiency rate of 87.08% with a loss of 2.96%. Additionally, Pachanawan *et al.* (2021) explored the effects of disc peg drum parameters on maize shelling performance within an axial flow shelling unit, revealing that increased rotational speed corresponded to higher shelling efficiency. Furthermore, a study by Steponavicius *et al.* (2018) on concave design for high-moisture corn demonstrated that a wider concave clearance resulted in decreased shelling efficiency. Notably, a collaborative effort within the Ban Pa Daeng Tai community, led by Jaichomphu *et al.* (2017) determined that 360 rpm was the ideal machine speed for a maize sheller. This effort yielded 85.80% maize seeds and 83.34% maize cobs when 20 kg of maize was processed. Subsequently, selling the seeds and cobs separately has proved more profitable for the community compared to selling unshelled corn.

Cumulatively, these research insights have catalyzed the development of diverse maize sheller designs, encompassing both large-scale and industrial options (Walke *et al*., 2017). Consequently, the objective was to design and develop an economically viable maize sheller that not only enhanced income but also expensed for farmer cooperatives.

Materials and methods

Maize shelling unit

The prototype maize sheller had a width, length, and height of 0.85 x 0.95 x 1.5 m, respectively, as shown in Figure 1. The sheller had two drums, each measuring 50 mm in diameter and 300 mm in length. The rod diameter was 3 mm, with a concave rod clearance of 20 mm and a concave length of 300 mm, as shown in Figure 2.

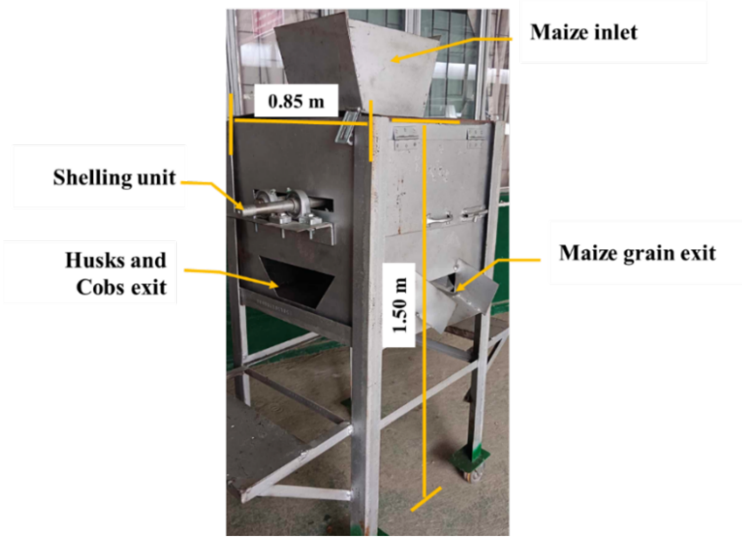

Figure 1. Maize shelling unit

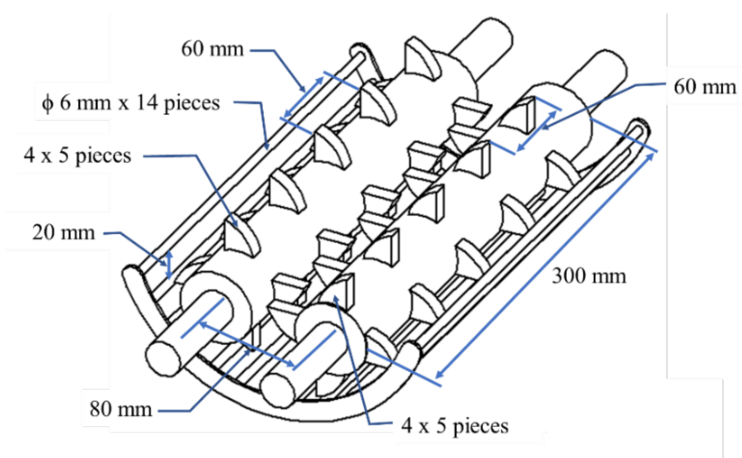

Figure 2. The maize sheller used in the test

Test factors and experimental design

Maize variety pacific 339 was employed in this study, and various factors were examined. These factors included three rotational speed levels for the sheller, specifically 450, 650, and 850 rpm, as well as four concave clearance levels, set at 10, 12, 14, and 16 mm. This experimental design aligned with the research conducted by Jaichomphu *et al*. (2017). These tests were conducted using a Randomized Complete Block Design (RCBD 3x4) for factorial experiments with three replicates.

Testing method

Each factor used 2 kg of maize. All samples were collected at the exit of the seeds and cobs. These collected materials were further processed to isolate the maize seeds. Subsequently, their weights were measured to calculate shelling efficiency and grain breakage. The economic system for the usage of the machine was then analyzed.

Data analysis

In this test, the shelling efficiency and grain breakage were used as the indicators in the statistical analysis. Then the results of the study were compared by Duncan's Multiple Range Test (DMRT). The economic system, including fixed costs (D), interest costs (I), break-even point (PBP), and total costs (TC), was analyzed.

Indicator values

Calculations for shelling efficiency and grain breakage were obtained from the Regional Network for Agricultural Machinery (RNAM, 1995). Shelling efficiency (SE) was expressed as a percentage and determined using Equation 1:

$$SE = (Wi/WT) \times 100 \quad (1)$$

Wi represents the weight of all the shelled grains (g), WT represents the weight of all fed grains (g), and Grain breakage (GB) represents the percentage of broken grains, as defined in Equation 2:

$$GB = (Wj/WR) \times 100 \quad (2)$$

Wj represents the weight of broken maize grains (g), while WR represents the weight of randomly selected broken grains (g).

The operation of the maize sheller, classified as an operational control expense, was subdivided into two components: fixed costs and variable costs. Fixed expenses encompassed depreciation, interest on investments, taxes, and insurance, while variable expenses comprised labor wages, electrical power usage for maize shelling machine, and maintenance costs. The economic analysis of maize sheller operation was conducted based on the following assumptions:

This cost analysis provides an estimation of depreciation (D) and can be expressed as the following equation.

$$D = (P-S)/N \tag{3}$$

P represents the initial price of the machine in baht, S stands for the machine's scrap value upon expiration or resale, also in baht, and N denotes the machine's useful life in years.

This cost analysis provides an estimate of the interest cost (I) associated with investment or the opportunity cost of investing. This can be represented in the following equation.

$$I = [(P+S)/2](r/100) \tag{4}$$

Where, r is the interest rate

The break-even analysis is a cost analysis aimed at estimating the payback period of the machine (PBP) based on an average cost of 1 baht per kilogram (36.18 THB = 1 USD). It involves assessing the relationship between the machine's price and the average annual net profit. This analysis can be expressed mathematically in the form of the following equation.

$$PBP = P/R \tag{5}$$

R represents the annual net profit in baht, and AC denotes the cost associated with using the machine in baht per kilogram. This relationship can be expressed mathematically in the form of the following equation.

$$AC = (FC/A) + (VC/Ct) \tag{6}$$

FC represents the fixed cost of operating the machine in baht per year, A signifies the annual working capacity of the machine in kilograms per hour, VC represents the variable cost of using the machine in baht per hour, and Ct denotes the machine's hourly working capacity in kilograms per hour. Both FC and VC can be calculated using the provided equation.

$$FC = D + I \tag{7}$$
$$VC = R\&M + E + L \tag{8}$$

E represents the cost of electricity for the main motor of the machine in baht per hour, L signifies the cost of labor for operating the machine in baht per hour, and R&M denotes the cost of repair and maintenance for the machine in baht per hour. Additionally, BEP, which stands for the break-even point, can be expressed mathematically as hours per year in the form of the following equation.

$$BEP = FC/(B\text{-}VC) \tag{9}$$

FC represents the fixed cost in baht per hour, and B is the employment rate, also in baht per hour. This cost analysis aims to estimate the total cost of the corn sheller (TC) and can be mathematically expressed through the following equation:

$$TC = (FC/X)+VC \tag{10}$$

where X is the working hours (hr)

Results

A comparative analysis of roller speed and concave clearance for maize shelling

The variances between roller speed (RS) and concave clearance (CC) in terms of shelling efficiency (SE) and grain breakage (GB) were analyzed. There were significant differences in both the SE and GB when the RS was adjusted. The interaction between the rotor speeds (RS) and concave clearance (CC) is shown in Table 1.

Table 1. Analysis of variance of rotor speed (RS) and concave clearance (CC) on shelling efficiency (SE) and grain breakage (GB)

Source of Variation	**SE**	**GB**
RS	42.343*	828.35*
CC	114.571*	37.02*
Block	1.927^{ns}	2.975^{ns}
RS*CC	52.118*	2.293^{ns}

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

The statistical analysis using Duncan's Multiple Range Test (DMRT) at a significance level of 0.05 showed that when the RS was 450 to 850 rpm, the differences in the SE of the rotor speed at 850 rpm were significant compared to the rotor speed of 450 and 650 rpm. When considering GB, the rotor speed of 850 rpm differed significantly from the rotor speed at 450 rpm, as shown in Table 2.

Table 2. Comparison results of the statistical averages of shelling efficiency (SE) and grain breakage (GB) using various rotor speeds (RS)

RS (rpm)	**SE**	**GB**
450	79.28^{a}	3.23^{a}
650	80.82^{b}	10.80^{b}
850	82.05^{c}	10.89^{b}

The same letter denotes no statistical difference

When the CC was increased from 10 to 16 mm, no statistically significant differences were observed in both SE and GB at the CC of 12 and 14 mm. When the GB was examined, no statistical differences were found at the CC of 12, 14 and 16 mm, as shown in Table 3.

Table 3. Comparison results of the statistical averages of shelling efficiency (SE) and grain breakage (GB) using various concave clearance (CC)

CC (mm)	**SE**	**GB**
10	89.1^{c}	12.07^{b}
12	82.10^{b}	10.82^{a}
14	81.74^{b}	10.79^{a}
16	75.24^{a}	9.88^{a}

The same letter denotes no statistical difference

The influence of rotor speed and concave clearance on shelling efficiency

Shelling efficiency was investigated in relation to the concave clearance (CC) and rotor speed (RS) and it was found that the average shelling efficiency reached a peak of 82.05% at the RS of 850 rpm. The speeds of 650 rpm and 450 rpm also exhibited high levels of efficiency at 80.82% and 79.28%, respectively. The analysis showed that at the CC of 10 mm, the average shelling efficiency reached its maximum at 89.1%, with subsequent reductions observed for CC of 12 mm, 14 mm, and 16 mm, which yielded shelling efficiency of 82.10%, 81.74%, and 75.24%, respectively. The obtained results demonstrated the significance of RS and CC as influential factors, as indicated by a P-value below 0.05, highlighting the relationship between RS and CC (Figure 3) in relation to shelling efficiency.

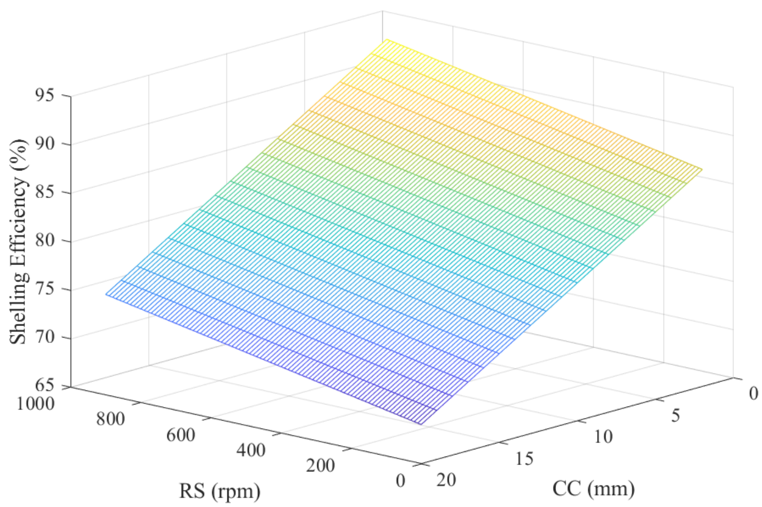

Figure 3. Influence of rotor speed (RS) and concave clearance (CC) on shelling efficiency (SE)

The influence of rotor speed and concave clearance on grain breakage

When RS was adjusted to 450 rpm, GB exhibited an average value of 3.23%. Subsequently, upon adjusting the shelling RS to 650 rpm and 850 rpm, the average GB increased by 10.80% and 10.89%, respectively. The CC of 10 mm, 10 mm, 12 mm, 14 mm, and 16 mm displayed average GB values of 12.07%, 10.82%, 10.79%, and 9.88%, respectively. These results underscore the significance of RS and CC as influential factors, as evidenced by a P-value below 0.05, signifying the relationship between RS and CC (Figure 4) in relation to grain breakage.

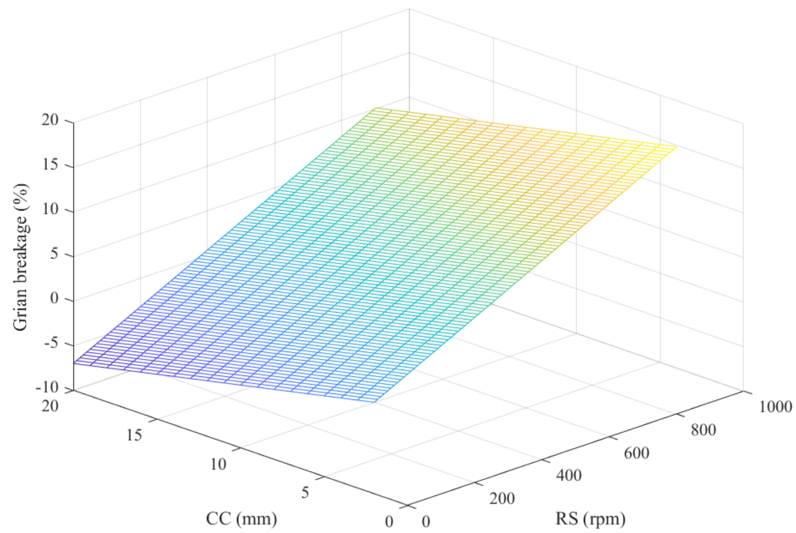

Figure 4. Influence of rotor speed (RS) and concave clearance (CC) on grain breakage (GB)

Economic analysis results for the operation of the maize sheller

The cost of machine utilization, the break-even point, and the break-even point of the manual labor for corn shelling were calculated. It was determined that maize could be shelled by one worker at an average rate of 300 kg/hr. The cost of shelling maize was calculated at approximately 300 baht per day (8.27 USD/day), assuming an 8-hour workday, resulting in a cost of 8 baht/kg. The maize sheller was tested, and data were collected for economic evaluation.

The cost of utilizing the maize sheller encompassed expenses related to machine usage, fixed costs, sheller depreciation, interest costs, and machine price. The machine price was fixed at 24,000 baht (662.1 USD), with a calculated scrap value of 10% of the machine price. The machine's useful life was estimated at 5 years, with an annual interest rate of 10%. Repair and maintenance costs were set at 10% of the machine price for every 100 hours of operation. Electricity costs for the main motor were calculated at 14.96%, equivalent to 4.155 baht per hour. Electricity was priced at 3.6 baht per kWh (as per the standards of the Metropolitan Electricity Authority), and labor costs for operating the maize sheller were established at 37.5 baht per hour for individuals working 8 hours a day and receiving a minimum daily wage of 300 baht (8.27 USD). The survey revealed that the average shelled maize price was approximately 1 baht per kilogram.

The payback period was determined by considering the annual work break-even point. Given a working capacity of 300 kg/hr, the annual working hours totaled 365 hr, equivalent to the number of days of use per year. Assuming 8 hours of daily operation, the break-even point was calculated at 65.74 days per year. Consequently, the payback period was found to be 0.18 years or 2 months.

Discussion

A comparative analysis of roller speed and concave clearance for maize shelling

The highest shelling efficiency was achieved at a speed of 850 rpm. The elevated rotor speed generated a substantial hitting force, leading to reduced shelling resistance and consequently, higher SE and GB. Saeng-ong *et al.* (2015), Srison *et al.* (2016), found that an increase in rotor speed resulted in both the SE and GB increasing. Moreover, a concave clearance (CC) of 10 mm resulted in the highest shelling efficiency. The increased CC decreased SE and GB because greater clearance provided more space between the drums and concave, and reduced shelling force. Srison *et al.* (2016), Pachanawan *et al.* (2021) found that an increased concave clearance resulted in decreased SE and GB.

The influence of rotor speed and concave clearance on shelling efficiency

A reduced shelling resistance led to higher SE, which was attributed to the elevated rotational speed that applied increased force to the maize. Saeng-ong *et al.* (2015), Yu *et al.* (2015) and Srila *et al.* (2021) found that increased rotor speed (RS) tended to increase shelling rates. The expanded concave clearance (CC) lessened the impact force between the sheller teeth and the concave, resulting in a decrease in SE. Tunhaw *et al*. (2019), Pachanawan *et al*. (2020) found that an increase in CC led to decrease in SE.

The influence of rotor speed and concave clearance on grain breakage

The current study revealed that an increase in rotor speed (RS) led to a corresponding increase in grain breakage (GB). This effect was attributed to the heightened speed, which generated a forceful impact between the cracker's teeth and the grating, consequently resulting in increased grain breakage. This finding aligns with prior research conducted by Steponavicius *et al.* (2018), Al Sharifi *et al.* (2019), and Pachanawan *et al*. (2021), all of whom observed that an elevated rotor speed tended to increase grain breakage rates. Conversely, an increase in concave clearance (CC) reduced maize shelling. This outcome concurs with the results reported by Wacker (2005) and Kiniulil *et al*. (2017), who likewise found that variations in concave clearance did not significantly impact grain breakage.

Economic analysis results for the operation of the maize sheller

The break-even point for utilizing the maize sheller was determined to be 6,878 kg/year, which corresponds to an annual usage duration of 1,578 hours, equivalent to 0.18 years or 2 months.

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