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Development and optimization of a fresh lotus embryo piercing machine

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ABSTRACT

Crispy lotus seeds were a healthful snack suitable for all ages and commonly available in modern commerce outlets. The production process requires removing the lotus embryo before crisping. Traditionally, manual labor separated the embryo from the lotus seeds. Operators use specialized equipment to separate the lotus embryo from the lotus seeds. This requires a lot of work time and may cause injury to the operator due to the equipment used. Many research works have created machines to help process lotus seed products, but their performance is lacking. This research focused on creating and developing a fresh lotus seed embryo removal machine to improve precision and reduce seed damage during extraction. The prototype machine included a frame construction, a seed feeding tray, a piercing unit, and a PLC control panel. Two types of needles are used to pierce the lotus embryo. The sharp needle produced the best results when tested with sharp and blunt needles at piercing speeds of 16.7, 25.0, and 33.3 mm/s. The findings revealed a 91.7% success rate in embryo removal, 13.9% seed splitting, 2.8% seed damage, a processing capacity of 0.7 kg/hr, and an energy usage of 0.4 kW-hr. Economic engineering research revealed that employing the lotus embryo removal machine for 1,440 hours per year resulted in an average cost of 83.3 THB per kilogram, a 26.4-month payback period, and a breakeven threshold of 1,233.3 hours per year (863.3 kg per year). The prototype performed at least twice as quickly as manual labor (0.3 kg/hr).

Keywords: Lotus, Lotus seeds, Lotus embryos, Piercing machine

INTRODUCTION

The lotus plant is highly versatile, with all parts, from roots to leaves, being edible [1, 2]. Fresh lotus seeds, in particular, have been processed into OTOP products and developed into food items for modern trade markets. Lotus seeds are highly nutritious and possess therapeutic properties [3-5]. The bitter embryo at the seed's center resembles a sprout with two arrow-shaped leaves, one short and one long, ranging from yellow-green to dark green, measuring 1-1.5 cm in length and approximately 2 mm in diameter. Traditionally discarded, lotus seed embryos were later recognized for their medicinal properties, including alleviating irritability, insomnia, and oral infections, reducing blood pressure, dilating coronary arteries in arterial stenosis, and relieving thirst after hematemesis [6-8]. Consequently, their use increased, particularly in capsules and lotus seed tea.

In Thailand, community-based businesses process lotus seeds by peeling them with a fruit knife, manually removing the shell and membrane, and extracting the embryo with a toothpick or skewer (Figure 1). The seeds and embryos are then separated for further processing. This step relied on manual labor, posing a risk of cuts and requiring considerable time and effort [9]. Researchers in Thailand have investigated the use of lotus seed de-shelling and piercing machines [10-12]. Still, their lack of accuracy and performance, along with their high seed damage rate, have prevented their adoption. While lotus seed de-shelling machines used abroad [13-15] are available, their high cost and incompatibility with the physical characteristics of Thai lotus seeds have prevented imports. Lotus seed piercing machines have not been used either domestically or internationally. Therefore, research was conducted to develop a new industrial-grade lotus seed piercing machine, providing a model for entrepreneurs to study and improve the machine's accuracy and suitability for Thai-grown lotus seeds.

MATERIALS AND METHODS

2.1 Examined the key details for the design.

a) Studied the physical characteristics of lotus seeds.

This study aimed to determine the physical characteristics of peeled fresh lotus seeds, providing data for designing seed-feeding trays and making

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necessary machine adjustments, including seed diameter and length (Figure 2). A random sample of 100 lotus seeds was measured with a Mitutoyo 530-118 vernier caliper (made in Japan). The seed diameters ranged from 9 to 14 mm, averaging 11.2 ± 1.1 mm, and lengths ranged from 14 to 19 mm, averaging 16.7 ± 0.9 mm. Compared to Langkapin et al. (2014) [10], the seeds in this study were smaller and rounder. The diameter and length were used to design the width and height of the seed-feeding compartments in the packaging tray.

Figure 1 Manual method of peeling and piercing lotus seeds.

(a)Diameter (b) Length

Figure 2 Physical characteristics of lotus seeds.

b) Studied the optimal system for lotus seed piercing.

A literature survey revealed that Langkapin et al. (2014) [10] developed a fresh lotus seed piercing machine with a cam-controlled mechanism and a conveyor system powered by a Geneva wheel. The system achieved a 70% piercing rate, 13.3% seed damage, and a processing capacity of 1.2 kg/hr. The fully mechanical design resulted in high seed damage and low accuracy. To improve precision and reduce seed damage, key concepts from this machine were incorporated into a new design featuring a Programmable Logic Controller (PLC).

2.2 Design and construction of the prototype machine

Using the design data, a fresh lotus seed piercing machine was developed using computer-aided design software [16] and mechanical and agricultural machinery design concepts [17]. The main components included the main frame structure, the seed feeding tray, the piercing unit, and the PLC control panel, as shown in Figures 3 and 4.

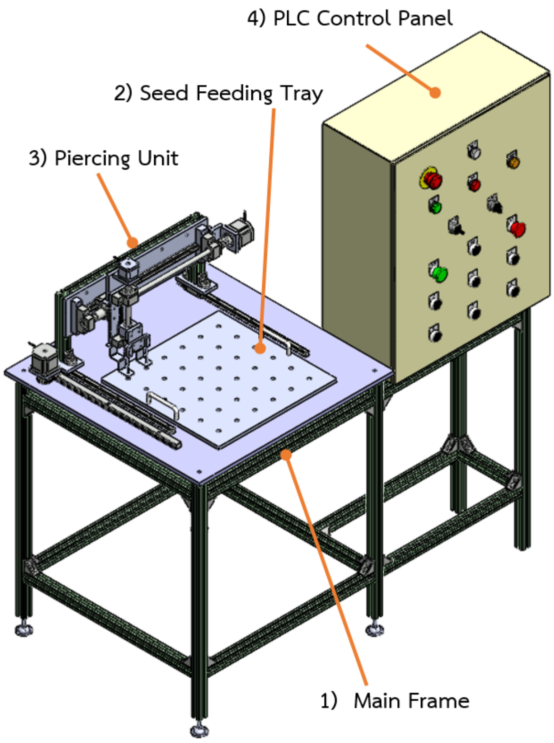

Figure 3 Prototype design using CAD software.

Figure 4 The prototype lotus seed piercing machine.

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The details of each component are as follows:

1. The main frame structure, made of 30 x 30 mm metal profiles, supports various components and is assembled with metal brackets, screws, and T-nuts. The frame measures 656 mm in width, 1,186 mm in length, and 800 mm in height. The seed tray and other components are positioned on top, with a 500 mm rack gear featuring 15 mm-wide teeth and 105 teeth and a 460 mm linear guide rail supporting the power system and drive components along the Y-axis. The PLC control panel is located on the right side of the frame.

2. The seed feeding tray, made of aluminum, holds peeled lotus seeds for piercing. It measures 425 mm in width, 425 mm in length, and 15 mm in height, with a handle for easy handling. The tray accommodates 36 seeds, arranged in 6 rows of 6 holes, spaced 65 mm apart. Each compartment is cylindrical, 14 mm in diameter, and 12 mm deep, with a bottom hole twice the size of the piercing needle, enabling it to pass through the tray.

3. Piercing unit: the piercing unit for the lotus seeds was mounted on a movable mechanism capable of movement along the X, Y, and Z axes. The coordinate system was defined using the right-hand rule. Design details are as follows:

The piercing unit's X and Y-axis moving device (Figure 5) features a Y-axis base that drives the piercing head along the X and Z axes. Using linear guides, the 10 mm thick aluminum base is fixed to the machine frame. A C-57STM03 stepping motor provides power, with a 15 mm wide, 25-tooth gear transmitting power to a rack gear on the Y-axis base, enabling 500 mm forward and backward movement of the piercing head. The X-axis movement is driven by another C-57STM03 motor, transferring power to a 500 mm ball screw, with a linear guide controlling its position for the left-right movement of the piercing head.

The Z-axis moving device, shown in Figure 6, enables vertical movement of the piercing head. It consists of a linear guide and a 180 mm ball screw mounted on a 12 mm thick aluminum base. A C-57STM03 stepping motor powers the system, allowing the piercing head to puncture two seeds simultaneously. The stainless-steel needle, 3 mm in diameter and 130 mm in length, is used for the puncturing process. As the piercing head rises, seeds are ejected from the needle by an aluminum push mechanism at the frame's bottom. The tests utilized two types of needles: blunt-ended and sharp-ended.

4. The PLC control panel, measuring 256 mm in width, 530 mm in length, and 750 mm in height, was mounted on the right side of the machine frame. It controlled the piercing machine's operation and featured an intuitive interface with status indicators and safety functions. The main control circuit used a Mitsubishi FX3U-32M PLC with 16 inputs and 16 outputs. The panel included relays, a switching power supply, circuit breakers, magnetic contactors, fuses, and terminal blocks. The front of the panel had a pilot bulb, push-button switches, various controls, and an emergency switch [18, 19].

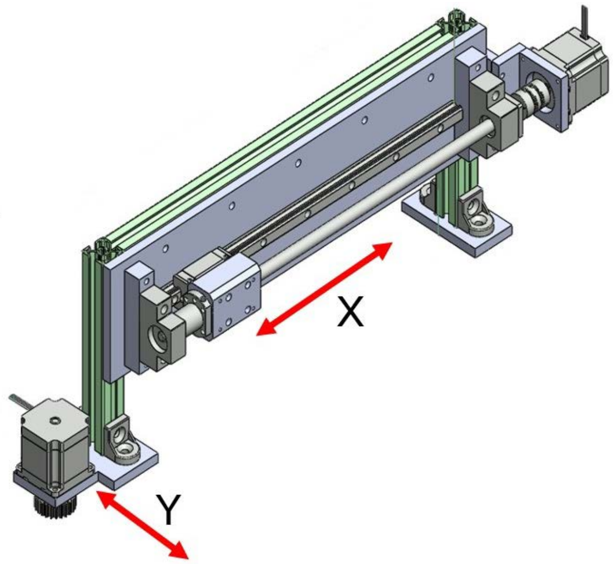

Figure 5 The X and Y axis moving device of the piercing unit.

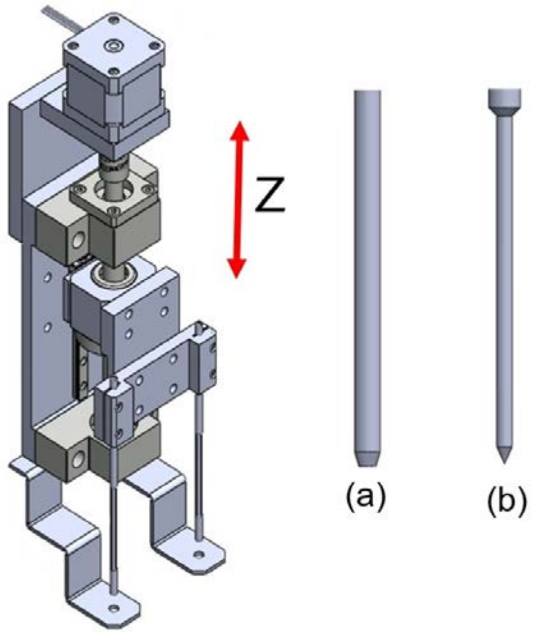

Figure 6 The Z-axis moving device and piercing needle: (a) blunt-tipped and (b) sharp-tipped.

The operation of the lotus seed-piercing machine commences with the operator placing the lotus seeds into the seeding tray and positioning the tray in the upper compartment of the machine. The white status light on the control panel is illuminated upon activating the circuit breaker and power switch. Pressing the Reset button once initiates the movement of the X, Z, and Y-axes through inductive proximity switches, enabling the detection and setting of the home position for all three axes. The switch is then set to "Auto" mode, and pressing the Start button activates

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the green status light on the control panel. Subsequently, the piercing head moves to the designated position to pierce the seeds in the tray. Upon completion of the operation, the piercing head automatically returns to the home position, and the seed tray is removed to collect the pierced seeds.

2.3 Testing and performance evaluation of the prototype machine

After the prototype machine was modified to address defects, its performance was tested and evaluated, including the quality of lotus seed piercing. The study's performance indicators included piercing percentage, seed splitting percentage, seed damage percentage, operational capacity, and electrical energy consumption, calculated using the following equation:

The lotus seed piercing percentage was calculated using Equation (1).

$$c_t = \frac{W_1}{W} \times 100 \qquad (1)$$

Where:
C_t = lotus seed piercing percentage (%)
W_1 = weight of pierced lotus seeds (kg)
W = total weight of lotus seeds (kg)

The percentage of lotus seeds split into two halves was calculated using Equation (2).

$$S_g = \frac{W_2}{W} \times 100 \qquad (2)$$

Where:
S_g = percentage of lotus seeds split into two halves (%)
W_2 = weight of lotus seeds split into two halves (kg)

Damaged seeds were identified based on any visible cracks or defects from the original seed during testing. The percentage of seed damage was calculated using Equation (3).

$$D_g = \frac{W_3}{W} \times 100 \qquad (3)$$

Where:
D_g = percentage of seed damage (%)
W_3= weight of damaged seeds (kg)

The operational efficiency was calculated using equation (4).

$$C_a = \frac{W_1}{T} \qquad (4)$$

Where:
C_a = actual operational efficiency (kg/hr)
T = total operating time, Including the seed feeding time (hr).

Electrical energy consumption was calculated using equation (5).

$$P = \frac{IVt}{1{,}000} \qquad (5)$$

Where:
P = the electrical energy consumption (kW-h)
I = the current (Amperes)
V = the voltage (Volts)
t = the time (Hours)

During the test, manually dehulled and size-sorted Padum variety lotus seeds were used, with diameters ranging from 9 to 14 mm (average 11.4 ± 1.2 mm) and lengths from 14 to 20 mm (average 17.1 ± 0.8 mm) based on a sample of 50 seeds. Initial tests identified an optimal pulse frequency for driving the stepper motors on all axes, ranging from 4,000 to 10,000 Hz, ensuring smooth operation. Test speeds for the stabbing head were selected based on motor-driven velocities of 16.7, 25.0, and 33.3 mm per second. Two types of needles, sharp-tipped and blunt-tipped, were used. Each test involved 30 seeds, with three replications per condition. For each trial, the total work time, weight of successfully punctured seeds, weight of seeds split into two halves, weight of damaged seeds, and voltage were recorded. Statistical analysis was conducted at a 95% confidence level using one-way ANOVA, followed by Duncan's New Multiple Range Test (DMRT) for multiple comparisons. A paired-samples t-test ($p < 0.05$) was used to assess significant differences between groups.

2.4 Economic analysis.

a) Analysis and evaluation of average costs.

The cost assessment for using the lotus seed punching machine assumed entrepreneurs purchased it to replace manual labor. It included both fixed and variable costs. Fixed costs comprised machine depreciation (calculated using the straight-line method over a 5-year lifespan) and the opportunity cost of capital (at a 10% interest rate). Fixed expenses that do not vary with processing volume, such as insurance, taxes, storage, and transportation, were excluded. Variable costs, determined by the amount of lotus seed processed, included labor, electricity, maintenance, and repair costs.

b) Payback Period Analysis.

This analysis estimated the time required for the investment in the lotus seed machine to be paid back, calculated by dividing the initial investment cost by the expected net benefits over 5 years.

c) Break-Even Point Analysis.

The break-even point was calculated by comparing the costs of using the prototype seed-peeling machine to those of manual labor [20].

RESULTS AND DISCUSSION

The lotus seeds obtained after testing the prototype machine's performance are shown in Figure 7(a). Figure 7(b) shows the peeled lotus seeds. Figure 7(c) depicts seeds with easily removable embryos, while Figure 7(d) shows seeds split into two halves and those damaged during testing. The test results of the prototype machine, based on the type of needle

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and the average speed of the piercing head, are presented as follows.

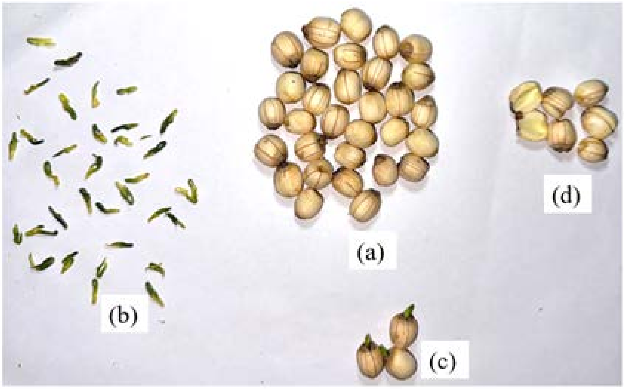

Figure 7 Performance test results of the lotus seed peeling machine: (a) lotus seeds after peeling, (b) peeled embryos, (c) partially peeled lotus seeds, and (d) lotus seeds split into two halves and damaged.

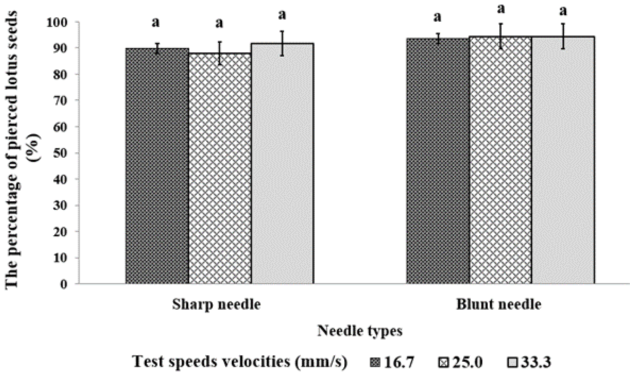

Figure 8 The percentage of lotus seed core removal at various needle types and average piercing speeds. (In each treatment, means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan's multiple range tests.)

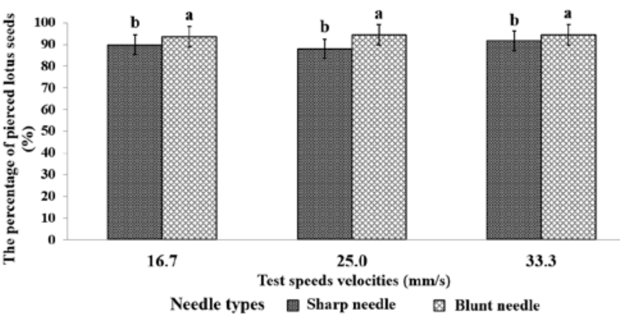

Figure 9 The percentage of lotus seed core removal at different piercing speeds and needle types. (In each treatment, means with the same letter are not significantly different at $p \leq 0.05$, as determined by pairwise t-tests.)

3.1 The percentage of pierced lotus seeds.

When tested with various needle types and average head speeds, the lotus seed piercing machine demonstrated a piercing rate of 88.0-94.4%. The statistical analysis showed no statistically significant differences in the piercing percentage at the 0.05 significance level between using sharp and blunt needles at various head speeds. As depicted in Figure 8, this finding suggests that either type of needle may be utilized at any head speed without affecting the piercing performance. According to the findings, the piercing percentage increased somewhat with more incredible head speeds and was comparable for both needles.

Figure 9 shows that the blunt needle performed better than the sharp needle at all tested speeds. The sharp needle achieved a piercing rate of 88.0-91.7%, while the blunt needle ranged from 93.5-94.4%, due to the blunt needle having a larger cross-sectional area in contact with the lotus embryo than the sharp needle. The optimal needle type and head speed should be selected based on additional research criteria, which will be discussed later.

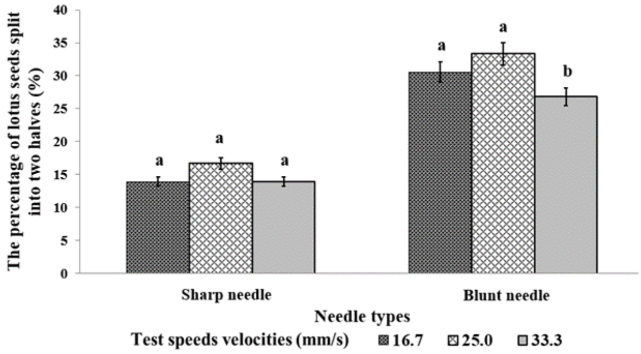

Figure 10 The percentage of lotus seeds split into two halves based on the type of needle and the piercing speed. (In each treatment, means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan's multiple range tests.)

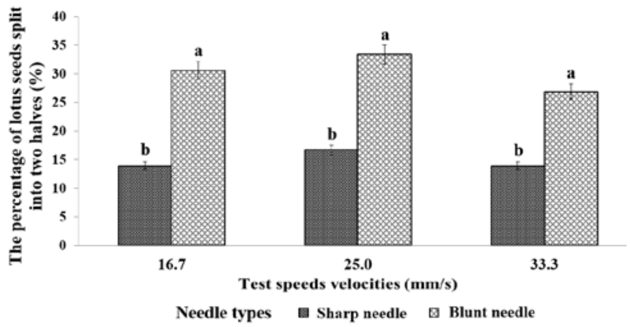

Figure 11 The percentage of lotus seeds split into two halves at different piercing speeds and needle types. (In each treatment, means with the same letter are not significantly different at $p \leq 0.05$, as determined by pairwise t-tests.)

3.2 The percentage of lotus seeds split into two halves.

Statistical analysis in Figure 10 showed no significant differences at the 0.05 level in the percentage of lotus seeds split into two halves when using the sharp needle across various head speeds. However, significant differences were found with the blunt

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needle. The sharp needle split 13.9-16.7% of seeds, while the blunt needle split 26.9-30.6%. Figure 11 showed that the blunt needle consistently resulted in more seeds split across all speeds. As shown in Figure 12, both whole and split seeds can be processed into crispy lotus seeds, with no price difference reported.

(a) (b)

Figure 12 Shows dried lotus seeds: (a) split seeds [21] and (b) whole seeds [22].

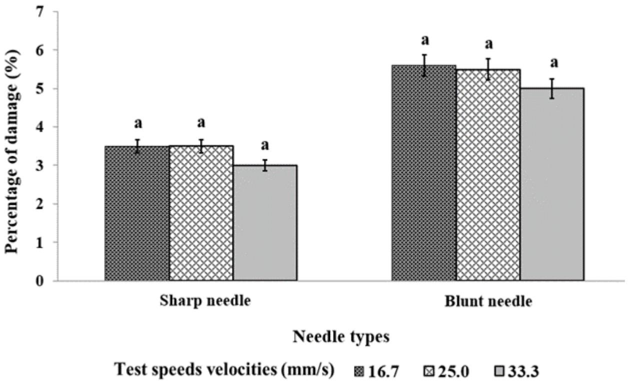

Figure 13 The percentage of damage at different types of needles and the piercing speed. (In each treatment, means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan's multiple range tests.)

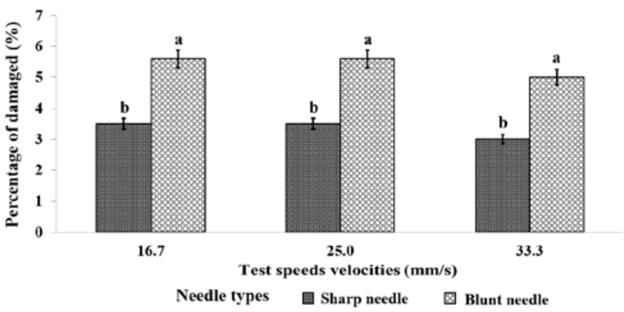

Figure 14 Damage percentage at different piercing speeds and needle types. (In each treatment, means with the same letter are not significantly different at $p \leq 0.05$, as determined by pairwise t-tests.)

3.3 Percentage of damage.

Figure 13 shows that both blunt and sharp needle head types yielded similar results. Damage percentage slightly decreased with increased puncture head speed, but statistical analysis found no significant differences at the 0.05 level. Damage percentage decreased with increasing puncture head speed. Figure 14 revealed that the blunt-tipped head caused more damage than the sharp-tipped head at all speeds. The blunt-tipped head had damage rates of 3.7-6.5%, while the sharp-tipped head ranged from 2.8-4.6%. The lowest damage percentage, 2.8%, occurred with the sharp-tipped head at a speed of 33.3 mm/s.

3.4 Machine performance.

Statistical analysis revealed significant differences in machine performance at a 0.05 significance level across tests with both puncture head types and speeds (Figure 15). Results shown in Figure 16 indicated no significant difference in piercing capability between the two head types at all average speeds. Performance improved with increased head speed, with operational capacities ranging from 0.4 to 0.7 kg/hr for both heads.

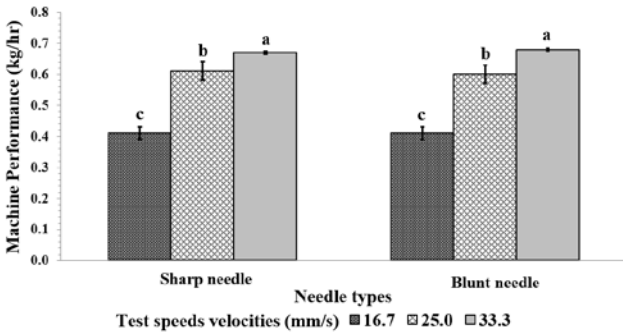

Figure 15 The work capacity of different types of needles and the piercing speed. (In each treatment, means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan's multiple range tests.)

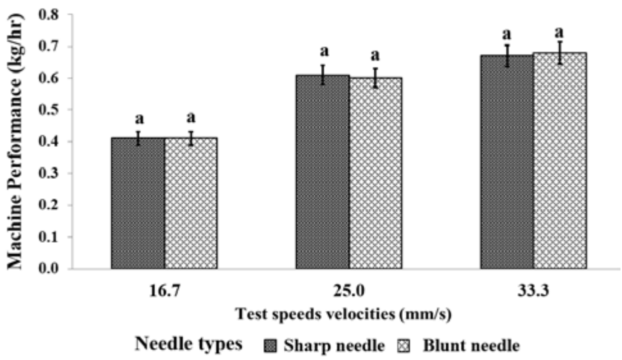

Figure 16 The work capacity at different piercing speeds and needle types. (In each treatment, means with the same letter are not significantly different at $p \leq 0.05$, as determined by pairwise t-tests.)

Based on operational capacity, piercing percentage, and seed damage, the sharp-tipped head at an average speed of 33.3 mm/s achieved the best performance, with a piercing efficiency of 91.7% and seed damage of only 2.8%. This configuration, with a

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0.7 kg/hr capacity, was selected for further economic engineering analysis.

3.5 Power consumption.

Statistical analysis (Figure 17) showed significant differences in the machine's electrical energy consumption at a 0.05 significance level across probe types and speed groups. Energy usage increased with higher probe speeds, ranging from 0.2 to 0.4 kW-hr. At the optimal speed of 33.3 mm/s, the sharp probe, which demonstrated the highest work capacity, consumed 0.4 kW-hr. This value was used for subsequent economic engineering analysis.

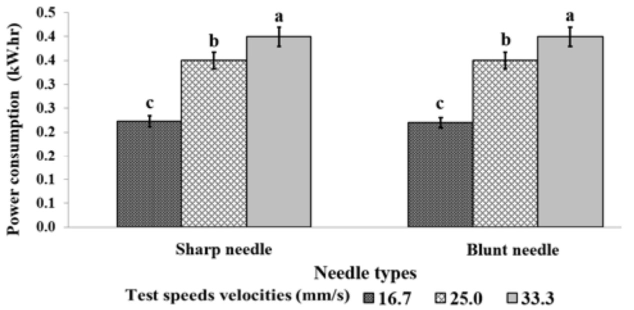

Figure 17 The electrical energy consumption at different types of needles and the piercing speed. (In each treatment, means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan's multiple range tests.)

3.6 Engineering economic analysis results.

The engineering economic analysis considered a single operator with a machine capacity of 0.7 kg/hr and energy consumption of 0.4 kW-hr, based on a prototype cost of 61,500 THB, a 5-year lifespan, and a 10% interest rate. The average price was 83.3 THB/kg, with a payback period of 26.4 months and a breakeven point at 1,233.3 hours/year (863.3 kg per year), assuming 1,440 hours of operation annually (8 hours/day for 6 months). These metrics were compared to manual labor by one worker.

CONCLUSIONS

Performance tests of the prototype lotus seed punching machine with a sharp-tipped head showed optimal operation at an average head speed of 33.3 mm/s, achieving a piercing rate of 91.7%, a production capacity of 0.7 kg/hr, a seed splitting rate of 13.9%, a seed damage rate of 2.8%, and an energy consumption of 0.4 kW-hr. Compared to Langkapin et al. (2014), the new machine had a 0.5 kg/hr lower work capacity, 10% less seed damage, and 21.7% greater accuracy. Despite this, it was more than twice as fast as manual labor. To enhance the processing speed significantly, the required production capacity can increase the number of tool headsets. The results met the study's objectives and offered operators a viable option for exploring an industry-level prototype.

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