# Compressive mechanical cracking of pili (*Canarium ovatum* Engl.) nuts: Concept and mechanism design

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**Abstract:** To increase the work capacity and ensure safety during the cracking of pili nuts, a mechanical pili nut cracker that used gradual compression for cracking was proposed and developed. This was a deviation from the traditional practice of applying impact for cracking pili nuts. The cracking unit of the pili nut cracker accomplishes gradual compression by a rotating assembly of discs and compression bars traveling along with an arrangement of cam rails. The cracker's performance was established using pili nuts at 9.9%, 11.6%, and 14.3% moisture levels (wet basis). The tests followed a single-factor three-level experiment where the performance indicators included cracking capacity, cracking efficiency, cracking recovery, whole kernel recovery, kernel damage, kernel losses, and purity of output. The machine performed satisfactorily using nuts dried for three days after depulping (MC = 11.6%). At this moisture level, the machine showed consistent and satisfactory performance in terms of cracking capacity (25 kernels min$^{-1}$), cracking efficiency (74.0%), cracking recovery (62.6%), and whole kernel recovery (84.3%). Modifications were recommended to further reduce kernel damage (30.6%) and kernel losses (37.4%) and to improve the purity of output (46.8%). It is recommended that the operating characteristics of the machine should be optimized to improve its performance. Furthermore, a dedicated feeding assembly and a more suitable separation method should be explored to further enhance the performance of the cracker.

**Keywords:** mechanical pili nut cracker, pili nut, nut cracker, pili nut processing, *Canarium ovatum* Engl.

**Citation:** Gallegos, R. K. B., D. C. Suministrado, P. M. Bato, R. M. C. Amongo, and R. B. Saludes. 2022 Compressive mechanical cracking of pili (Canarium ovatum Engl.) nuts: Concept and mechanism design. Agricultural Engineering International: CIGR Journal, 24(3):176-189.

## 1 Introduction

Pili cracking is still done manually by a skilled worker called "*paratilad*". The *paratilad* uses bolo to cut the shell at its middle section to extract the kernel (Figure 1). This operation requires precision and control to avoid damaging the kernel. The cracking process is followed by the separation of kernels from the shells. It is also at this stage that sorting is performed. The whole kernels are separated from the damaged ones and the rotten and spoiled kernels are discarded. Aside from being tedious, this method has low capacity and is unsafe for unskilled workers. Furthermore, skilled paratilads are now scarce, especially during the peak season of pili processing (Gallegos, 2012).

Mechanizing the pili cracking operation has been the subject of several efforts made by different researchers and institutions (e.g. University of the Philippines Los Baños, Bicol University Research and Development Center, Samar State University). Although the cracking capacity has significantly improved, most of the machines developed registered low cracking efficiency and high kernel damage. Most of the machines developed attempted to simulate the manual cracking

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**Received date:** 2021-08-31 **Accepted date:** 2022-02-21

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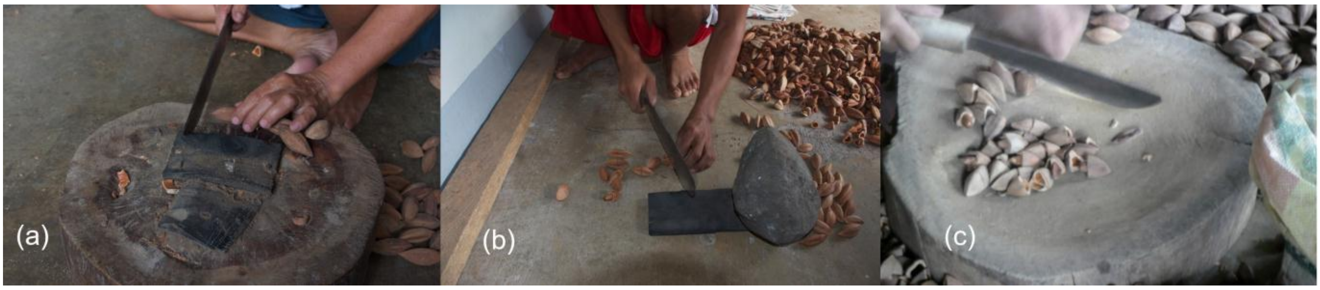
method of applying impact action to the shell to initiate cracking. Impact cracking using a bolo was observed to be effective when manually done. However, the success of this method was not successfully replicated in mechanical pili nut crackers. It was observed that impact cracking induces a high degree of damage to the kernels which significantly reduces the kernels' marketability (Malinis et al., 2003; Paras and Sumallo, 2004; Tuso et al., 2005, Ortega and Gabon, 2016).



(a) cracking using a wood platform and rubber mat; (b) cracking on the floor with rubber mat; (c) cracking using a wood platform with depression but without rubber mat

Figure 1 Some variations of the manual cracking method by *paratilads*

Little attempts had been made to investigate the possible merits of gradual compressive force application for pili nut cracking. Gradual compression and the use of compression rollers were found to be effective in nuts like macadamia (Liang, 1980; Sarig et al., 1980; Tang et al., 1982; Yangyuen and Laohavanich, 2018), palm nut (Ogundare and Ojolo, 2015), almond (Drees et al., 2017), walnut (Opobiyi et al., 2019) but few studies used this for pili nut (Adel et al., 2009). The development of a mechanical pili nut cracker that uses gradual compressive force is a viable solution to the high percentage of broken kernels produced by existing crackers. The use of a mechanical cracker for pili also addresses the concerns regarding the declining number of skilled laborers or *paratilads*. A mechanical pili nut cracker also offers a safer, faster, and more efficient way of extracting the kernels from the shell. This paper aims to demonstrate the use of gradual compressive force application for pili nut cracking as an alternative to the traditional impact force application.

## 2 Materials and methods

### 2.1 Design and fabrication of the mechanical pili nut cracker

Design criteria and considerations were first formulated before the design of the mechanical cracker. The results of the preliminary investigations on pili nut properties and a brief industry survey (Gallegos, 2012) were used to formulate the criteria and considerations used in designing the cracker. Manual cracking of nuts is still widely practiced to extract the kernel from the shell. But this method is laborious, has low capacity, and is dangerous to the operator. On the other hand, existing pili nut crackers still have shortcomings in terms of capacity, efficiency, and whole kernel recovery. Separation of kernels and shells after the cracking operation is still done manually as most pili nut crackers do not have separation units. These factors were considered in the design of the mechanical pili nut cracker.

Gradual compression of pili nuts along their longitudinal axes is proposed as an alternative method of cracking pili nuts. This idea was prompted by the observations of Gallegos et al. (2013) in their study of the compressive failure characteristics of pili nuts at different moisture content levels and loading orientations (transverse and longitudinal, see Figure 2).

From the same study, it was observed that drying rendered the shell brittle, i.e., the force and specific deformation required to initiate shell fracture increased and decreased, respectively, with a decrease in nut moisture content. The specific deformation required for fracture did not differ significantly among moisture levels in both loading orientations. For transverse compression, a nut needed to be compressed by about 5% of its height and a 1.55 kN of force to substantially inflict shell fracture. When compressed longitudinally, a nut needed about 2.83 kN of force and deformation of about 14% of its length to develop a fracture in its shell.

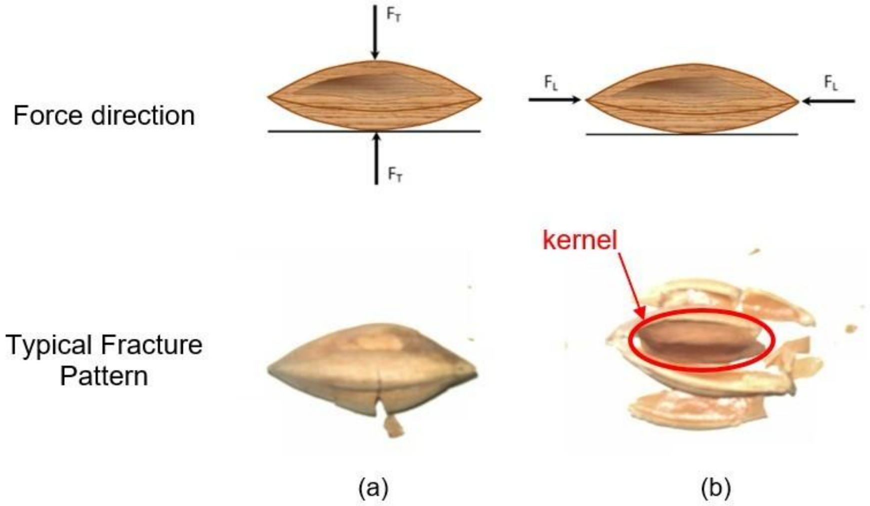


Figure 2 Typical fracture patterns of pili nuts due to gradual force application at their (a) transverse and (b) longitudinal axes

Figure 3 The fabricated mechanical pili nut cracker

In all moisture levels, longitudinal compression required significantly higher force and specific deformation for shell fracture than transverse compression. From a machine design perspective, this translates to a higher power requirement for the machine. However, it was observed during the tests that whole kernels were extracted from the nuts after compression (Figure 2). Furthermore, the shells were sufficiently fractured so that the whole kernel can be separated with less effort. Although transverse orientation required less force and specific deformation to initiate shell fracture, the kernel cannot be extracted with ease. The compressed nut should undergo subsequent cracking operations to extract the kernel. Furthermore, a high incidence of kernel damage was observed for nuts compressed transversely.

The fabricated mechanical pili nut cracker is shown in Figure 3. The individual components of the machine were selected and sized based on recommended design practices. Other relevant parameters were based on observations during the actual fabrication process. The design process was inherently iterative, as proven by the iterations made during the actual design process of the cracker.

### 2.2 Principles of operation of the mechanical cracker

The principle of operation of the developed cracking assembly is illustrated in Figure 4. The cracking unit is primarily composed of two rotating discs, nut buckets, compression bars, and two ring rails. Each disc is composed of metal plates with 12 equally spaced holes that house and guide the compression bars. The motion of the bars and buckets depends on the rotation of the discs relative to the ring rails.

The nut buckets receive the nuts to be compressed. The shape of the buckets allows the easy orientation of the nuts for compression. The buckets are suspended in between the discs using the compression bars. In addition, the buckets are free to rotate about the axis of the bars, ensuring their vertical orientation even if the two discs rotate.

The bars compress the nut inside the bucket. To accommodate the pointed end of the nuts, a cone-like depression was machined at the end of the bars. As the discs rotated, the bars are guided by the rails made of steel pipe. The rails act as cams that impart the lateral movement of the compression bars. The gap between the rails dictates the amount of deformation that should be made to initiate shell fracture to the nuts. Metal balls were attached to the bar ends to reduce friction between the bars and the rails. Furthermore, a return spring ensures that the bar slides along the rail at all times and acts as a retraction mechanism for the bar after the cracking process.

The cracking unit may be divided into three sections (Figure 5). The cracking process starts at the feeding section when a nut is fed into the nut bucket (Position 1 of Figure 4). Before the loaded bucket enters the cracking section, it passes through a series of protruding nylon cords that brushes and orients the nut for compression.

Assuming that the nut was properly oriented, the compression bars secure and compress the nut as they pass through the cracking section. Cracking is accomplished when the bars are forced to pass through a gap with decreasing clearance (Position 2 of Figure 4) until the needed deformation for fracture is reached. After the cracking process, the compression bars retract away from the cracked nut as they pass through a wider gap between the rails. The bucket then passes through the discharge section where it is struck by another nylon brush to release its contents into the cleaning unit. Further shaft rotation prepares the bucket for receiving the next nut from the feeder. The cracking unit rotates at approximately 8 rpm (the bucket peripheral speed is 34 cm $s^{-1}$), which translates to a theoretical capacity of 96 nuts $min^{-1}$. Figure 6 shows the cracking assembly loaded with nuts.

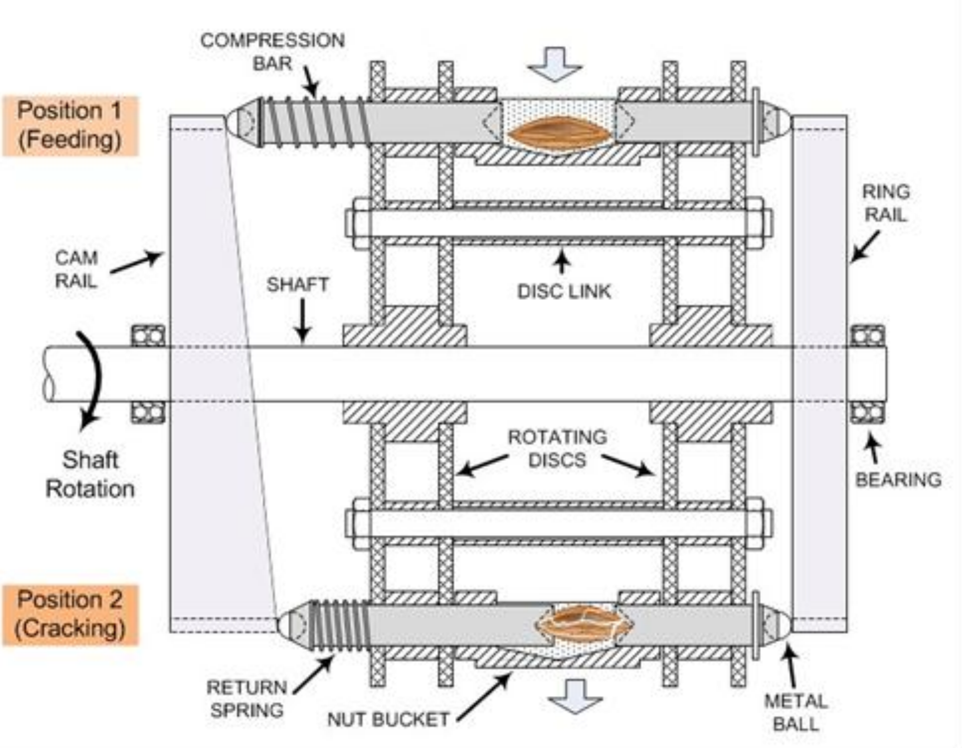


Figure 4 Main parts and operation of the cracking assembly

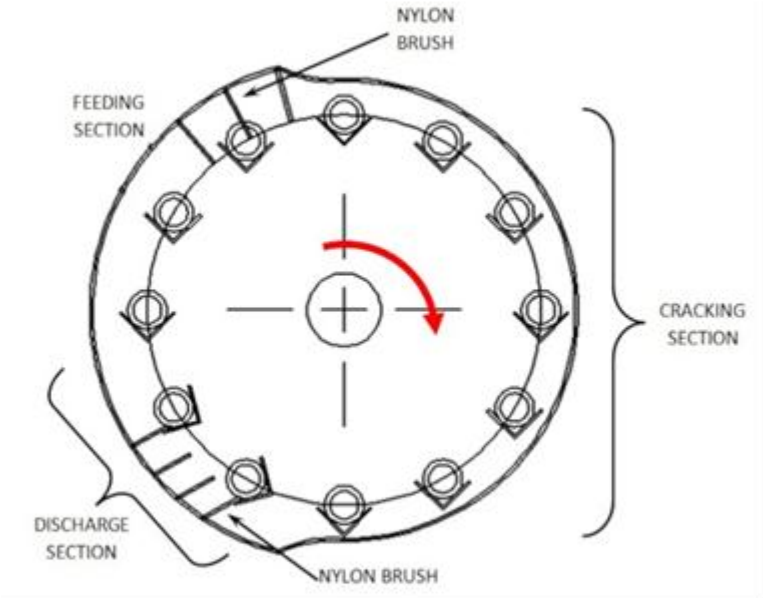


Figure 5 Main sections of the cracking assembly

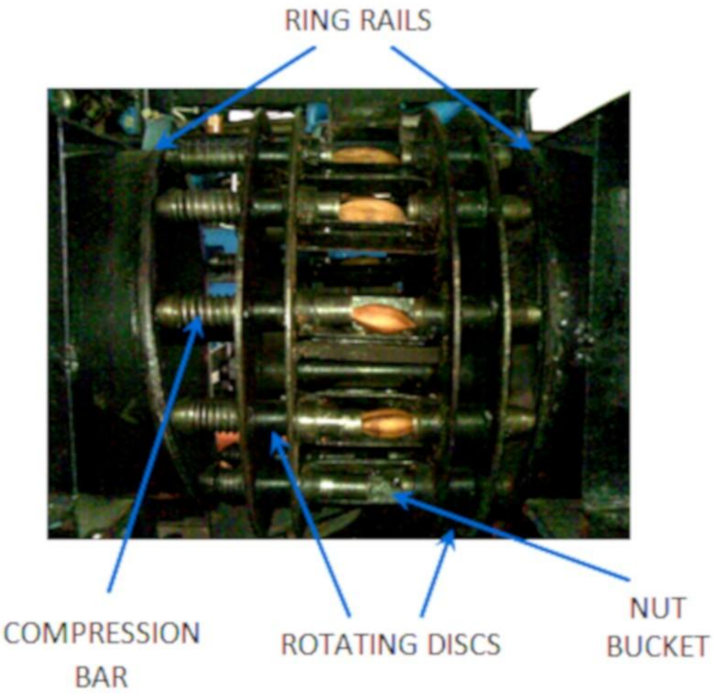


Figure 6 The cracking assembly loaded with pili nuts

### 2.3 Test and evaluation of the mechanical pili nut cracker

Tests and evaluation procedures were performed to establish the performance of the prototype and evaluate its operational features. No industry standard specifications and methods of the test were available for pili nut crackers when this research was conducted. The definitions, equations, and methods stated herein were adopted and were modified from Philippine standard specifications (PAES 220:2004) and standard methods (PAES 221:2004) of test for peanut sheller (Agricultural Machinery Testing and Evaluation Center, 2004a, 2004b) and the standard methods of test for coffee pulper (Agricultural Machinery Testing and Evaluation Center, 2011).

The cracker's performance was established by using nuts of different moisture levels. Fresh pili fruits of different varieties and sizes were harvested from trees along the Pili Drive of the University of the Philippines Los Baños (14.1648 ° N, 121.2413 ° E). The nuts were conditioned to three levels of moisture content. To obtain these levels, the nuts were sun-dried for three different durations – 2 days, 3 days, and 4 days. In the absence of a standard method for moisture content determination of pili nuts, the procedure followed came from ASAE S410.1 DEC1982(R2008) (ASAE Standards, 2008) and PAES 221:2004. The samples, each with five replicates, were exposed to an oven temperature of 103℃ for at least 72 hours. The nuts which were dried for two days, three days, and four days have moisture contents of 14.3%, 11.6%, and 9.9%, respectively.

Before the actual tests were performed, a running-in test was first made. The machine was fed with an ample number of nuts for cracking. Adjustments of different parts were made until a stable machine operation was achieved and the recommended machine settings were established. The recommended way of feeding the nuts to the machine was also practiced during the running-in test.

## 2.4 Experimental design

The performance test followed a single-factor three-level experiment. The machine was tested at three levels of nut moisture content. Three replicates were made for each moisture level, which translated to a total of nine runs for the entire test. The sequence of the nine runs was determined through a simple randomization process made before the runs. The differences in the cracker performance at these three nut moisture levels were determined by performing a One-Way Analysis of Variance (ANOVA) for each performance indicator. Indicators showing significant differences (at $p<0.05$) among moisture levels were subjected to Tukey's Honest Significance Test (HSD) to determine which moisture level showed significantly different results from the others. For each test run, the recommended settings of the machine were maintained.

In the performance indicators used in this study (see Table 1), the quantity of material handled by the cracker was expressed in terms of the number of nuts or kernels (by-piece). The "by-piece" basis was adopted because the machine has a relatively low capacity and counting the nuts or kernels is still manageable. When a large volume of nuts is handled and when the cracker has a high material capacity, the material flow may be expressed in terms of a "by-weight" basis. Purity, by its nature and definition, required the "by-weight" basis to be used. For each run, 200 randomly selected nuts of known weight were fed into the machine for cracking.

**Table 1 Indicators for establishing the performance of the mechanical pili nut cracker**

| Performance Indicator | Definition/Description | Equation/Method of Measurement |
|---|---|---|
| Input Capacity | The number of input nuts per unit loading time into the machines. The total loading time starts when the nuts are fed into the cracking unit and ends when the last nut is conveyed to the cracking unit of the cracker | $C_i = \frac{n_i}{t_i}$ (1)<br>where:<br>$C_i$ is the input capacity (nuts min$^{-1}$)<br>$n_i$ is the number of input nuts<br>$t_i$ is the total loading time (min) |
| Cracking Capacity | The ratio of the number of kernels received at the main kernel outlet of the machine to the total time of operation. The total operating time starts when the nuts are fed into the cracking unit and ends when all nut materials (shells and kernels) are discharged from the machine | $C_c = \frac{n_k}{t_o}$ (2)<br>where:<br>$C_C$ is the cracking capacity (nuts min$^{-1}$)<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$t_O$ is the total time of operation (min) |
| Total Kernel Losses (Absolute) | Summation of all kernel losses, i.e. uncracked loss, partially-cracked loss, scattering loss, and separation loss | $n_{TL} = n_{uc} + n_{pc} + n_{sc} + n_{se}$ (3)<br>where:<br>$n_{TL}$ is the total number of kernels lost during the operation<br>$n_{uc}$ is the number of kernels from uncracked nuts<br>$n_{pc}$ is the number of kernels from partially-cracked nuts<br>$n_{sc}$ is the number of scattered kernels<br>$n_{se}$ is the number of kernels received from all shell outlets |
| Uncracked Loss | The ratio of the quantity of kernels that remained in their shell to the total kernel input. Uncracked nuts are those that do not show any cracks after the nuts were fed into the cracking unit. | $L_{uc} = \frac{n_{uc}}{n_k + n_{TL}} \times 100$ (4)<br>where: |

| | | |
|---|---|---|
| | | $L_{uc}$ is the uncracked loss (%)<br>$n_{uc}$ is the number of kernels from uncracked nuts<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_{TL}$ is the summation of kernel losses |
| Partially-Cracked Loss | The ratio of the quantity of partially-cracked nuts to the total kernel input to the cracker. Partially–cracked nuts are those that showed cracks after the cracking operation but the kernel cannot be extracted easily unless the nuts are manually or mechanically- cracked in subsequent operations | $L_{pc} = \frac{n_{pc}}{n_k + n_{TL}} \times 100$ (5)<br>where:<br>$L_{pc}$ is the partially- cracked loss (%)<br>$n_{pc}$ is the number of kernels from partially- cracked nuts<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_{TL}$ is the summation of kernel losses |
| Scattering Loss | The ratio of the quantity of kernels that fell around the base of the machine to the total kernel input. Scattered kernels are those that came out of the machine but were not conveyed through the main kernel and shell outlets. They may come out from the unguarded openings of the machine. | $L_{sc} = \frac{n_{sc}}{n_k + n_{TL}} \times 100$ (6)<br>where:<br>$L_{sc}$ is the scattering loss (%)<br>$n_{sc}$ is the number of scattered kernels<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_{TL}$ is the summation of kernel losses |
| Separation Loss | The ratio of the quantity of kernels that came out from all shell outlets to the total kernel input. | $L_{se} = \frac{n_{se}}{n_k + n_{TL}} \times 100$ (7)<br>where:<br>$L_{se}$ is the separation loss (%)<br>$n_{se}$ is the number of kernels received from all shell outlets<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_{TL}$ is the summation of kernel losses |
| Cracking Efficiency | The ratio of the quantity of kernels that came out from all outlets to the total kernel input | $L_{se} = \frac{n_k + n_{sc} + n_{se}}{n_k + n_{TL}} \times 100$ (8)<br>where:<br>$E_c$ is the cracking efficiency (%)<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_{sc}$ is the number of scattered kernels<br>$n_{se}$ is the number of kernels received from all shell outlets<br>$n_{TL}$ is the summation of kernel losses |
| | Can also be computed by deducting the percent uncracked loss and percent partially-cracked loss from 100% | $E_c = 100 - L_{uc} + L_{pc}$ (9)<br>where:<br>$E_c$ is the cracking efficiency (%)<br>$L_{uc}$ is the percent uncracked loss (%)<br>$L_{pc}$ is the percent partially-cracked loss (%) |
| Cracking Recovery | The ratio of the number of kernels that came out of the main kernel outlet to the total kernel input | $R_c = \frac{n_k}{n_k + n_{TL}}$ (10)<br>where:<br>$R_c$ is the cracking recovery (%)<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_{TL}$ is the summation of kernel losses |
| hole Kernel Recovery | The ratio of the number of whole kernels to the total quantity of kernels that came out of the main kernel and shell outlets. Whole kernels are those that do not contain any fissures or cracks. A kernel is considered whole even if it bears scratches in its testa or outer covering. | $R_{wk} = \frac{n_{wk} + n_{ws}}{n_k + n_s} \times 100$ (11)<br>where:<br>$R_{wk}$ is the whole kernel recovery (%)<br>$n_{wk}$ is the number of whole kernels from the main kernel outlet<br>$n_{ws}$ is the number of whole kernels from all shell outlets<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_s$ is the number of kernels received from all shell outlets |

| | | |
|---|---|---|
| Mechanically-Damaged Kernels | The ratio of the quantity of broken and or severely- scratched kernels to the total quantity of kernels that came out of the main kernel and shell outlets. | $D_k = \frac{n_{dk} + n_{ds}}{n_k + n_s} \times 100$ (12)<br>where:<br>$D_k$ is the percent of mechanically- damaged kernels (%)<br>$n_{dk}$ is the number of mechanically- damaged kernels received from the main kernel outlet<br>$n_{ds}$ is the number of mechanically- damaged kernels received from all shell outlets<br>$n_k$ is the number of kernels received from the main kernel outlet<br>$n_s$ is the number of kernels received from all shell outlets |
| Purity | The ratio of the total weight of clean kernels to the total weight of kernels and impurities that came out of the main kernel outlet. | $P = \frac{W_{ck}}{W_{ck} + W_{im}} \times 100$ (13)<br>where:<br>$P$ is the purity (%)<br>$W_k$ is the weight of clean kernels from the main kernel outlet (g)<br>$W_{im}$ is the weight of impurities received from the main kernel outlet (g) |

## 3 Results and discussion

### 3.1 Mechanics of the cracking assembly

#### 3.1.1 Theoretical cracking capacity

The design and arrangement of the cracker components suggest that for every revolution of the assembly, the number of cracked nuts will be equal to the number of loaded buckets. Therefore, the theoretical cracking capacity $C_{th}$ of the cracking assembly (i.e., all buckets are loaded) is given by the equation:

$$C_{th} = N \times n \tag{14}$$

where:

$C_{th}$ is the theoretical cracking capacity (nuts $\text{min}^{-1}$);

$n$ is the number of nut buckets;

$N$ is the speed of rotation of the assembly (rpm).

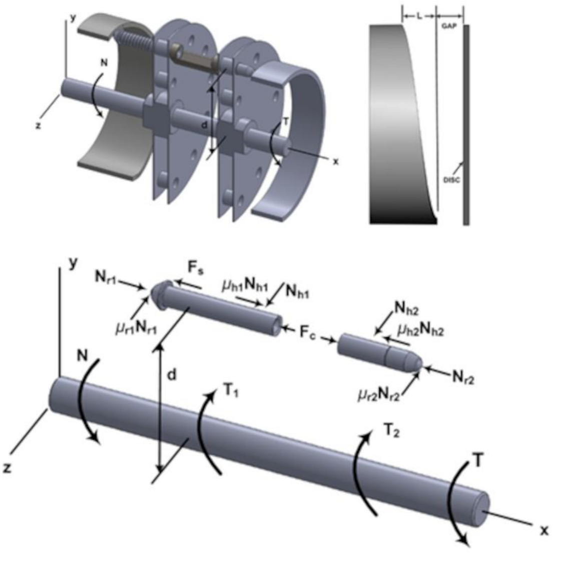


Figure 7 Free body diagram for estimation of cracking power requirement

Thus, the capacity of this machine may be increased by increasing the number of nut buckets, $n$, and the speed of rotation of the assembly, $N$. The cracker has 12 nut buckets and is rotated at approximately 8 rpm, which translated to a $C_{th}$ of 96 nuts $\text{min}^{-1}$. This capacity is twice the capacity of the manual cracking method. Furthermore, such speed was found to be the most suitable for convenient manual feeding during the cracking operation.

#### 3.1.2 Estimation of the power requirement of the cracking process

The power needed for the cracking process is an important parameter to be determined. It is usually the basis of sizing the different components of the cracker especially the transmission components like shaft, bearings, belt and chain drives, etc. The specific design of the assembly requires that the power be expressed in terms of the speed and torque needed to rotate the cracking assembly. Figure 7 may be used as a free-body diagram to derive the power.

In deriving the torque for the whole cracking assembly, it is assumed that the weight of the buckets and the nuts is negligible relative to the magnitude of other forces. Furthermore, friction in the bearings supporting the shaft is assumed to be negligible. The power needed may be determined by examining the case of a single bucket suspended between two compression bars

If the cracking assembly has an angular speed $N$ and rotates in the direction shown, it is evident that the total torque $T$ is the sum of the torques $T_1$ and $T_2$, which are the torque required to rotate discs 1 and 2, respectively, i.e. $T = T_1 + T_2$. The compression bars are separated from the shaft center by the distance $d$. To have an estimate of $T1$ and $T2$, the forces acting on compression bars 1 and 2 should be determined.

For Compression Bar 1, summing forces along the $z$-axis, $x$-axis, and torque about the $x$-axis, yields the following relations, respectively:

$$N_{h1}=\mu_{r1}N_{r1}$$

$$N_{r1}+\mu_{r1}N_{h1}=F_c+F_s$$

$$T_1=N_{h1}\times d$$

Similarly, for Compression Bar 2,

$$N_{h2}=\mu_{r2}N_{r2}$$

$$N_{r2}+\mu_{r2}N_{h2}=F_c+F_s$$

$$T_2=N_{h2}\times d$$

Manipulating the previous relations gives rise to the following equations:

$$T_1 = d \times \left( \frac{F_c + F_s}{\frac{1}{\mu_{r1}} + \mu_{h1}} \right)$$

And

$$T_2 = d \times \left( \frac{F_c}{\frac{1}{\mu_{r2}} + \mu_{h2}} \right)$$

It is assumed that the frictional properties of both rails are the same. The same can be said for both holes, i.e. $\mu_{r1} = \mu_{r2} = \mu r$ and $\mu_{h_1} = \mu_{h_2} = \mu_h$. The torque for a single nut can be expressed as:

$$T_{nut} = d \times \left( \frac{2F_c + F_s}{\frac{1}{\mu_r} + \mu_h} \right)$$

The preceding equations should be evaluated for different values of $F_s$ since the spring force depends on the degree of compression at each loaded bucket and will reach its maximum value when its original length was compressed by the cam rail height $L$. If $n_{loaded}$ buckets are loaded, the total torque required to rotate the discs along the rails is given by:

$$T_{total} = n_{loaded} \times d \times T_{nut} \quad (15)$$

For a conservative estimate of $T_{total}$, $F_s$ should be maximized and it should be assumed that all the $n$ buckets are loaded and experience the same degree of compression. Assuming that the frictional properties of the surfaces and the spring properties are known, one can estimate the theoretical power needed by multiplying $T_{total}$ by $N$. Gallegos et al. (2013) observed that a nut needs about 2.83 kN of force and should be compressed by at least 14% of its length to exhibit fracture which is sufficient to release the kernels.

### 3.2 Separation unit and transmission system

The separation or cleaning assembly functions to free the kernels of shells and other impurities. Designing the cleaning assembly was a challenging endeavor. Most cleaning mechanisms rely mainly on density and size differences to separate mixture components. Unfortunately, the sizes of the kernels and the shells are comparable. Further observation of the kernel and shell shapes and sizes revealed that the kernels were almost cylindrical and most of the shell fragments were almost flat. This prompted the development of an oscillating tray that contains slots with variable clearances. With sufficient oscillation, the flat shells were oriented so that their thinnest dimension passed through the narrow clearances. Since the kernels were almost cylindrical, they just roll over in the tray until they met the gap that allowed them to pass through. Impurities larger than the kernels (uncracked and partially-cracked nuts and large shells) were conveyed at the end of the tray (Figure 8).

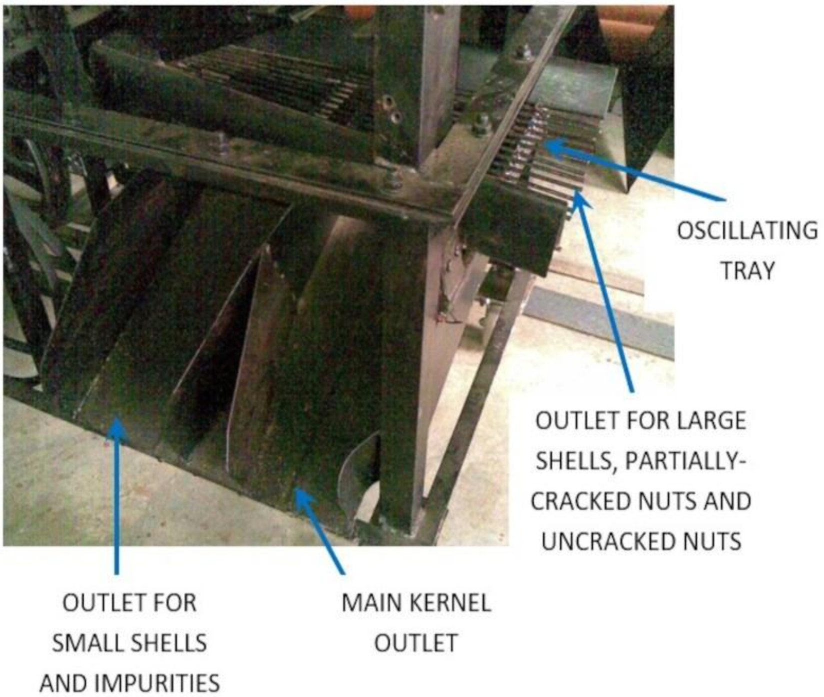


Figure 8 Basic parts of the separation assembly of the cracker

The transmission system (Figure 9) of the cracker distributed the power from the prime mover to the different machine components. The machine was powered by a 5 hp single phase electric motor with a rated speed of 1725 rpm.

Figure 9 Components of the power transmission system of the cracker

Using a belt and pulley transmission, the power was received by a countershaft to distribute it to the oscillating tray and other components. The belt and pulley combination was chosen to have a speed reduction ratio of 2.5. The power required by the cracking unit was delivered through a chain and sprocket system and a gearbox. The chain and sprocket reduced the countershaft speed by a factor of 1.75 at the input shaft of the gearbox. The gearbox (which was directly coupled to the cracking assembly) had a speed reduction ratio of 50:1, allowing the cracking assembly to rotate at about 8 rpm.

### 3.3 Performance of the mechanical pili nut cracker

Table 2 summarizes the performance characteristics determined at three levels of nut moisture content. It should be noted that the performance indicators included in this section were determined while an operator manually fed the nuts into the machine. Some values of the performance indicators may vary when the machine is tested by another operator.

**Table 2 Performance of the mechanical pili nut cracker at three levels of nut moisture content**

| Performance Indicator | Nut Moisture Content, % (wet basis) | | |
|---|---|---|---|
| | 9.9 | 11.6 | 14.3 |
| Input Capacity (nuts min$^{-1}$) | $41^{a}$ | $45^{a}$ | $40^{a}$ |
| Cracking Capacity (kernels min$^{-1}$) | $21^{b}$ | $25^{b}$ | $20^{b}$ |
| Cracking Efficiency (%) | $68.4^{c}$ | $73.3^{c}$ | $74.8^{c}$ |
| Cracking Recovery (%) | $54.2^{d}$ | $61.6^{d}$ | $54.3^{d}$ |
| Whole Kernel Recovery (%) | $50.6^{e}$ | $82.5^{f}$ | $77.2^{f}$ |
| Mechanically-Damaged Kernel (%) | $62.1^{g}$ | $32.0^{h}$ | $33.9^{h}$ |
| Uncracked Loss (%) | $27.4^{i}$ | $22.8^{ij}$ | $19.0^{j}$ |
| Partially-Cracked Loss (%) | $4.2^{k}$ | $3.9^{k}$ | $6.2^{k}$ |
| Separation Loss (%) | $14.2^{l}$ | $11.7^{l}$ | $20.6^{m}$ |
| Scattering Loss (%) | nil | nil | nil |

Note: N.B. In a row, means followed by the same letter are not significantly different at $p<0.05$ by HSD Test.

#### 3.3.1 Input and cracking capacities

Input and cracking capacities are closely related parameters and therefore are discussed jointly. The observed input capacity was about half the cracker's theoretical capacity of about 96 nuts min$^{-1}$. The values obtained were comparable to the manual method of cracking about 46 nuts/min (Gallegos, 2012). Similarly, the cracking capacity was slightly higher than the manual shelling operation capacity of about 19 kernels min$^{-1}$. The decrease in capacity was attributed to the rate of feeding which was determined by the operator. It was observed during the runs that some buckets were unfilled as the operator fed the nuts. This consequently lowered the capacity of the sheller. The observed differences in input and cracking capacities were not significantly different ($p$<0.05) among moisture levels. This means that the sheller exhibited the same capacities regardless of the moisture level of the nuts that it handled.

### 3.3.2 Cracking efficiency

This parameter indicates how well the machine breaks the shell for the kernel to be extracted. Results show that cracking efficiency is independent of nut moisture content. This translates to the consistent efficiency of the cracker regardless of nut moisture content. It was observed that one source of inefficiency was when the operator missed the buckets and the nuts just fell into the oscillating tray. Moreover, the nuts experienced vibration even if they were carefully positioned in the buckets. This happened when the first batch of nuts was cracked, disturbing and disorienting the newly-fed nuts. Nuts that were not properly oriented were not fully cracked and discharged as partially-cracked nuts with crushed ends (Figure 10). Furthermore, some nuts were short and were not fully compressed to fracture. The cracking clearance set was wide for short nuts but too narrow for larger nuts. Decreasing the clearance eventually compressed the larger kernels, which was undesirable.

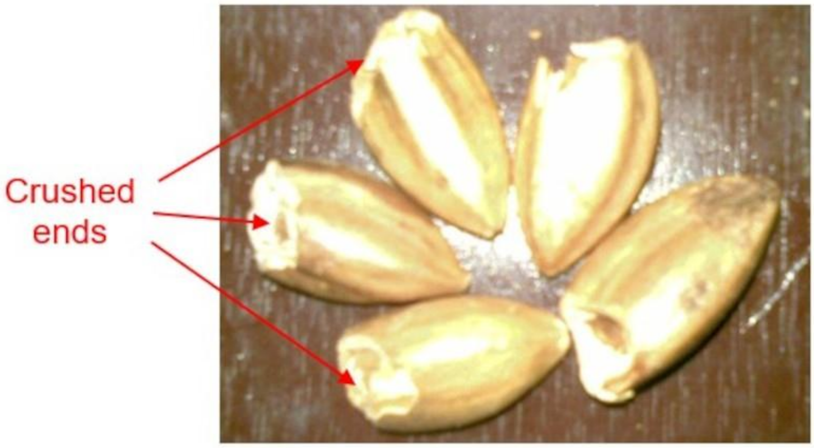


Figure 10 Partially-cracked nuts discharged from the machine

### 3.3.3 Cracking recovery and kernel losses

Cracking recovery and kernel losses are two opposite but related performance indicators. Cracking recovery is a measure of the number of kernels obtained in the main kernel outlet. Any kernels not collected from the main kernel outlets are considered losses, i.e., high kernel losses translate to low shelling recovery.

The consistency of the cracker's performance was again reflected in the values of cracking recovery, regardless of nut moisture content. The observed differences in this indicator were not significantly different ($p$<0.05) among moisture levels. The values of cracking recovery indicated that about half of the total kernel input was lost during the cracking operation. Kernel losses were the summation of uncracked loss, partially-cracked loss, separation loss, and scattering loss.

The bulk of the losses came from the combined uncracked and partially-cracked losses. This is related to the observed inefficiency of cracking. To reduce this loss, the cracking efficiency must be improved by designing a more suitable feeding mechanism and by reducing vibration during cracking. Separation loss also contributed significantly to the total losses. It was observed during the runs that the bulk of the separation loss came from the kernels that were conveyed into the outlet intended for large shells, uncracked nuts, and partially-cracked nuts (Figure 11).

Figure 11 Thick kernels (encircled in red) that were conveyed into the shell outlet

Most of the kernels that were conveyed to the shell outlets were thick which prevented them from falling into the main kernel outlet. This observation was reinforced by the significantly higher separation loss computed when the moist nuts (MC=14.3%) were fed into the machine. Moist nuts, in general, have larger dimensions than drier nuts.

It is worth mentioning that no scattering loss was recorded during the tests. This means that the material handling components of the machine were well-guarded against the possible loss of kernels.

### 3.3.4 Whole kernel recovery and mechanically-damaged kernels

Kernel quality after the operation is one important indicator of the cracker's performance. Moist kernels are more tolerant to mechanical damage. This was observed during the runs and reinforced by the significantly higher values of whole kernel recovery for moist nuts. Drier nuts are more brittle and are prone to breakage. This was also manifested in the magnitude of kernel damage observed during the tests. Although it is desirable to crack moist nuts to minimize kernel damage, kernels with high moisture content are susceptible to mold attacks if not dried immediately. The best quality of extracted kernels was observed from the nuts with a moisture content of about 11.6%. At this moisture level, most of the recovered kernels were whole and had little mechanical damage.

It was observed that one of the most common forms of kernel damage was kernel tip breakage which happened to long and dry kernels. This damage occurred during the cracking process when the compression cylinders reached the kernels. Damage may also be in the form of scratches, where the seed coat is torn and exposes the seed, albeit the kernel is whole and intact.

### 3.3.5 Purity of output

The purity of cracked kernels is the primary determinant of the performance of the separation assembly of the cracker. Ideally, the cleaning unit should free the kernels from impurities. The performance of the separation unit in terms of cleaning the kernels of impurities was consistent regardless of the moisture content of the materials that it handled. It was observed that more than half of the weight of the samples coming from the main kernel outlet was impurities. This was manifested in the values of purity which is less than 50%.

It should be emphasized that the interpretation of the computed values of purity should be accompanied by prudence. Purity values were expressed on a by-weight basis. Inspections made during the test revealed that shells, with thicknesses almost similar to the kernels, were the most common impurities conveyed into the main kernel outlet (encircled in red in Figure 12b). Although these shell fragments were very few compared to the kernels, their weight was significantly higher than that of the kernels. This resulted in apparent low values of purity.

Since the separation unit relied primarily on size differences to separate the kernels from impurities, it was unavoidable that impurities with sizes similar to the kernel size were discharged into the kernel outlet of the cracker.

(a) shell outlet (b) main kernel outlet where thick shells (encircled in red) were mixed with the kernels

Figure 12 Materials coming out of the different outlets

## 4 Conclusions

This paper proposed a novel method and a machine for cracking pili nuts. A mechanical pili nut cracker that uses gradual compression for cracking was developed as an alternative to the usual practice of applying impact for cracking pili nut. It was observed that gradual compression is a feasible method for individual cracking of pili nut provided it is done along the longitudinal axis of the nut.

The prototype’s performance showed great promise. The machine performed very well using nuts dried for three days after depulping (11.6%). At this moisture level, the machine showed consistent and satisfactory performance in terms of cracking capacity (25 kernels min$^{-1}$), cracking efficiency (74.0%), cracking recovery (62.6%), and whole kernel recovery (84.3%). Modifications are recommended to further reduce kernel damage (30.6%) and kernel losses (37.4%) and to improve the purity of output (46.8%). Based on the results of the study, the following specific recommendations are made to improve the performance of the mechanical pili nut cracker:

A dedicated and more appropriate feeding mechanism should be developed. The absence of a mechanical feeder significantly reduced the capacity of the machine.

A more appropriate cleaning mechanism should also be developed to further enhance the purity of the machine’s output.

An optimization study should be conducted to further enhance the performance of the cracker

## Conflict of interest

The authors declare that they have no conflict of interest.

## Acknowledgment

The authors extend their sincerest gratitude and appreciation to the Center for Agrifisheries and Biosystems Mechanization (BIOMECH), University of the Philippines Los Baños for partially providing the materials used in this work.

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