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DEVELOPMENT AND OPTIMIZATION OF PALM NUT CRACKING AND SEPARATING MACHINE

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Abstract

This study presents a locally manufactured palm kernel cracking and separating machine designed to address the challenges associated with traditional palm kernel cracking procedures, including discomfort, tension, labor intensity, time consumption, unnecessary costs, and complexity. The machine, equipped with a 3hp electric motor operating at a shaft speed of 1430rpm, demonstrated efficient performance by cracking 1kg of palm nuts in an average of 47.58 seconds. The palm nuts are divided into three categories: uncracked, partially cracked, and cracked, with average weights of 0.06kg, 0.08kg, and 0.85kg, respectively. Among the cracked palm nuts, unbroken kernels weighed 0.83kg, and broken kernels weighed 0.02kg. The machine attained a throughput capacity of 76kg/hr and a cracking efficiency of 85.32%. The utilization of MATLAB resulted in the creation of a predictive model for optimal cracking efficiency. This model revealed that 1kg of palm kernels fed into the machine yielded 0.88kg of broken palm nuts, 0.10kg of separated shells, 0.02kg of fibrous material, and an overall cracking efficiency of 88%. Compared to traditional manual cracking methods, this mechanized system provides a faster, less labor-intensive, and more productive method of palm kernel cracking.

Key Words- Locally developed, Optimization, Palm nuts, Cracking and Separation, MATLAB Program

1. Introduction

The palm kernel, a significant by-product of the palm tree (Elaeis guineensis Jacq), holds immense value for humanity and is highly sought after due to its oil content, suitable for direct consumption or raw material for various products. This plant cultivated in the rainforests part of Nigeria, West Africa, and other global regions where palm kernel cultivation is not the primary challenge; instead, the focus lies on producing high-grade kernels for supply to companies. The palm tree, the richest vegetable oil plant [1], comes in several types, offering multiple derivatives such as palm oil, palm kernel oil, palm kernel cake, fiber, palm wine, fatty alcohol, broom, and wood plank. The kernels and shells (see Figure 1) find extensive applications across industries, serving as raw materials for soap, cosmetics, livestock feeds (agriculture), medicine, foundry, and even as an energy source, among other uses. The palm tree produces fruits in bunches, varying in weight from 10 to 40kg, with individual fruits weighing between 60 to 70g [2].

Figure 1. Palm kernel nuts and shells

The continuous rise in global demand for palm kernel underscores its significance. The palm nuts, obtained from cracked palm kernels, undergoes milling to extract palm kernel oil, a crucial ingredient in soap, glycerin, margarine, candles, pomade, oil paint, polish, and medicine. Additionally, palm kernel oil plays a role in fuel and biodiesel production. The resulting kernel cake becomes a valuable ingredient in the production of livestock feeds, while the fibers find application as fuel in boilers [3]. Over the years, the extraction of oil from kernels has involved a diverse range of traditional, chemical, and mechanical processes [4].

Cracking palm nuts to extract kernels is a crucial stage that significantly influences the quantity and quality of kernel oil. This procedure can be carried out using either traditional or mechanical approaches [5]. The conventional method employs the impact principle, in which six nuts placed on a flat stone hammered using another stone to crack them. Typically carried out by women and children, this method is crude and results in slow, uneconomical, labour-intensive, and occasionally hazardous kernel recovery for the operator [6]. In addition to the challenges of drudgery, time consumption, and health hazards associated with this method, further winnowing may be required due to the substantial retention of fibre in the nuts [7].

The conventional mechanical cracking process typically employs a centrifugal mechanism. Nuts are introduced into the cracking chamber, where they encounter metal beaters rotating at high speeds.

These beaters impart impactful forces, causing the nuts to collide with a cracking ring. The nuts exhibit random orientations upon impingement on the chamber wall, undergoing repeated impacts through bouncing until they are discharged, either cracked or uncracked, albeit with a considerable incidence of kernel breakages. Understanding the minimum impact force required for efficient nut cracking is essential for enhancing the design of existing mechanical nutcrackers [8]. Consequently, the challenge lies in developing an efficient motorized palm kernel sheller that reduces processing time and costs while achieving equivalent functionality as existing models-a task that cannot be over-emphasised.

This research examines machinery for palm kernel nut cracking and reviews relevant literature. Recently, a range of prototypes and conceptual ideas for mechanized palm nut-cracking machines have been developed by researchers and engineers [9]–[18]. While advancing in palm nuts cracking operation, there are notable deficiencies in the existing processes. Notably, the high operational speed of current cracking devices necessitates design modifications to minimize mechanical damage and enhance product recovery. Addressing other shortcomings of existing crackers is imperative, such as the prevalence of uncracked nuts in the final product, attributed to inappropriate spacing of blow bars and a high nut feeding rate into the cracking chamber. Furthermore, breaking of cracked nuts may result from excessive impact post-shell removal [19].

Farmers in several southern Nigerian districts where palm kernels are widely planted face challenges related to the cost and time required to process this vast agricultural produce. Additionally, the geographical distance between these farmers and processing plants often compels them to resort to traditional cracking methods, exposing them to unintentional injuries, such as finger impacts with the cracking stone. This project intends to improve existing technology by constructing optimized and portable palm nuts cracking and separation equipment to address these stated issues faced by remote farmers. The objective is to improve efficiency while reducing costs, ultimately increasing the profitability of rural palm kernel farmers. The research has three particular goals: (1) design and develop a palm kernel cracking and separation machine; (2) optimize its performance efficiency; and (3) compare the experimental and optimized performance efficiencies.

2. Methodology

The palm kernel cracking and separation apparatus comprises of five principal components: the in-feed unit, cracking unit, discharge outlet, sorting unit, and drive unit. The in-feed unit, which includes the feed hopper and in-feed elbow, is made of stainless steel in the shape of a frustum inclined at a horizontal angle of 60° to allow for kernel unhindered fall, to reduce kernels jamming at the throat and to allow for self-cleaning. The in-feed elbow, a half-parabolic tube made from mild steel with a total length of 457mm, includes both the hollow section and the elbow structure. The cracking chamber is a hollow cylindrical tube that houses a rectangular (channel-shaped) cracking hammer in the centre made of mild steel and has minor and major diameters of 340 X 410mm and a length of 350mm. The chamber's back surface is bored with a 50mm diameter for the drive shaft to pass through to the chamber's core. The cracking mechanism works by impacting the walls of the cracking chamber with the 8mm thick cracking hammer, helping the cracking process on the kernels. The cracking process is achieved by the impact force exerted on the kernels by the cracking hammer (8mm thick) against the walls of the cracking chamber.

The discharge unit is positioned directly beneath the cracking chamber, featuring an opening measuring 180 × 100mm in width and height. This design facilitates the simultaneous passage of multiple cracked nuts, preventing congestion at the discharge point and thereby improving sorting efficiency. The sorting unit comprises a rectangular metallic mesh with uniformly spaced rectangular grooves of 10mm diameter. This component connects to the nut discharge unit of the cracking chamber, spanning dimensions 335mm in length, 106mm in width, and 50mm in height. As an agitated basket, the sorting unit oscillates forward, backward, and sideways, induced by vibrations from the electric motor. The chosen diameter of the mesh grooves is smaller than the average kernel seed diameter (12mm), ensuring that the kernel nuts remain on the sorting route without being expelled. The sorting tray is inclined at a 20° angle to the horizontal, facilitating the smooth sliding of kernel seeds over the mesh grooves while effectively discharging the shells from the grooves.

The driven unit comprises essential components, including the prime mover (electric motor), two two-way pulleys, and the belt drive system. The choice of the V-Belt for power transmission in this project stems from its exceptional qualities, such as optimal traction, efficient speed transfer, effective load distribution, and extended service life. A singular V-belt (A54) with dimensions of 8mm thickness, 1418mm length, and 13mm width was employed. The primary function of the electric motor is to propel the rotor at a high speed. A single-phase dual-capacitor electric motor, boasting three (3) horsepower and rotating at 1430 revolutions per minute, was selected for this purpose. The pulleys assume a pivotal role in power transfer from the electric motor shaft to the cracking mechanism shaft, propelling the centrifugal impact cracking drum via the V-belts. Two pulleys are used: a smaller pulley with a 60mm diameter connected to the electric motor and a larger pulley with a 136mm diameter attached to the cracking drum's shaft. The preference for mild steel pulleys was deliberate, chosen for their capacity to facilitate changes in the direction of force, lighter weight compared to cast iron pulleys, higher strength and durability, and a reduced tendency for failure or breakage.

The machine's frame serves as its fundamental structure, supporting the various components, as depicted in Figure 2 and Figure 3 for the assembled and exploded views, respectively. Its crucial role lies in providing stiffness and stability during operation. Specifically designed to withstand shocks and vibrations, the frame ensures the machine's stability, preventing twisting or instability during use. This design consideration contributes to the overall firmness and stability of the machine throughout its operational lifespan. Because of its ideal properties such as hardness, relative toughness, rigidity, and good machining characteristics, high mild steel was selected as the material for the frame's construction for optimum performance.

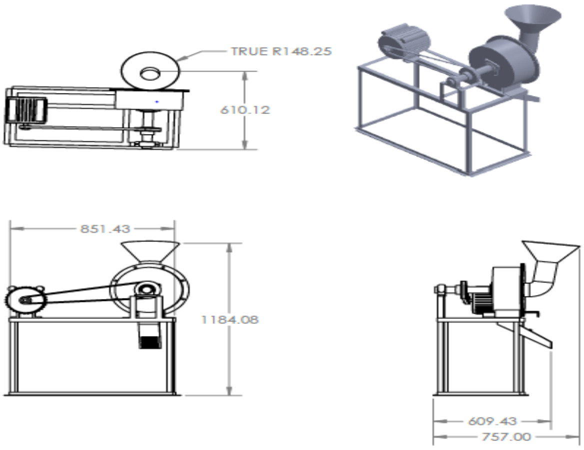
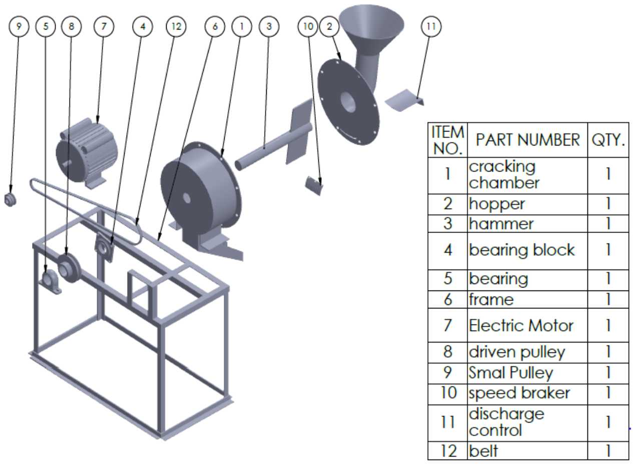


Figure 2. The assembled drawing of the machine



ITEM NO.	PART NUMBER	QTY.
1	cracking chamber	1
2	hopper	1
3	hammer	1
4	bearing block	1
5	bearing	1
6	frame	1
7	Electric Motor	1
8	driven pulley	1
9	Smal Pulley	1
10	speed braker	1
11	discharge control	1
12	belt	1

Figure 3. The exploded view of the machine

2.1 The Design Analysis and Calculations

2.1.1 The Cracking Energy

The cracking process is achieved by the impact force exerted on the kernels by the cracking hammer. This impact force is generated by the kinetic energy of the cracking hammer, thus,

Kinetic energy of kernels = Impact energy of kernels on the cracking wall, Eq (1).

$$\text{K.E} = \frac{1}{2}\text{m}v^2 = \text{Impact Energy} \quad (1)$$

Where m = mass of kernel and v = velocity

But, Impact energy on the cracking wall = Work required to deform a kernel is given as,

$$\text{Work, } \text{W} = \frac{F}{2} \times x \quad (2)$$

Where F = force applied and x = displacement

The force applied on the kernel is given as,

$$\text{Impact force, } \text{F} = \text{P} \times \text{r} \quad (3)$$

Where P = impact load and r = ratio of the stress under impact to the direct stress or the deformation under impact to the corresponding deformation given by Eq (4).

$$\text{r} = \frac{\sigma'}{\sigma} \quad (4)$$

$$\text{where, } \sigma' = \frac{2P}{A} \text{ and } \sigma = \frac{P}{A} \quad (5)$$

Therefore, $\text{r} = 2$, and $\text{F} = 2\text{P}$

Interestingly, the kinetic energy of the kernel equals the impact energy also known as the deformation energy. Thus,

The deformation Energy,

$$W = \frac{1}{2}mv^2 = Px \quad (6)$$

The product ($\text{P}x$), defined as the energy of deformation, is given from experimental results as 0.9012 and 2.0015Nm for Dura and Tenera nuts respectively.

2.1.2 The Shaft Design

Shafts are designed on the basis of strength, rigidity and stiffness.

Radius of gyration (k) is given as

$$k = \frac{h}{\sqrt{12}} = 0.289h \qquad (7)$$

Where, h = total height of the cracking hammer

But moment of inertia about the x-axis (I_{xx}):

$$I_{xx} = mk \qquad (8)$$

Also, $I_{xx} = \frac{bh^3}{12}$ (9)

The tangential force (F) to the axis of rotation is given by the relation:

$$F = m\alpha \qquad (10)$$

Where α is the angular acceleration; whose maximum value is given as

$$\alpha = \omega^2 r \qquad (11)$$

The angular velocity, ω is determined as:

$$\omega = v/r \qquad (12)$$

Also, $\omega = \frac{2\pi N}{60}$ (13)

$$F = m\omega^2 r \qquad (14)$$

Torque, $T = Fr$ (15)

The minimum power requirement,

$$P = T\omega \qquad (16)$$

2.1.3 Force to crack palm kernel nut (F)

The cracking strength of palm kernel as determined from [20] as:

$F = A \times S$

Where, A = area of palm kernel cracking,

S = strength and F = cracking force

2.1.4 The sorting unit

The basic considerations for the sorting unit are:

Size of machine: length (L) = 1m, width (B) = 0.46m, height (H) = 1m

Amplitude of vibration required on the sorting tray, $\delta_{ST} = 5 \times 10^{-3} m$

Force, $F = ke$ (17)

But F = W for static deflection under self-weight, and $e = \delta_{ST}$

$$W = k\delta_{ST} \qquad (18)$$

$$W = \rho V g \qquad (19)$$

But equivalent stiffness of the machine structure,

$$k_{eq} = \frac{3EI}{L^3} \qquad (20)$$

Since the sorting tray is a cantilever structure.

Where E = Flexural stiffness of material used.

L = length of sorting tray and the machine support frame.

I = moment of inertia of the whole machine, I_{XX}

Therefore, $E = \frac{KL^3}{3I}$

2.1.5 The power for vibration

Taking $\omega_n = \sqrt{\frac{g}{\delta_{ST}}}$ (21)

$$r = \frac{\omega}{\omega_n} \qquad (22)$$

But transmissibility of amplitude:

$$\frac{X}{Y} = \frac{1}{\sqrt{(1-r^2)^2 + (2\xi r)^2}} \qquad (23)$$

ξ= damping ratio = 2% = 0.02 for steels

$Y = \delta_{ST} = 0.005$m

$$X = \frac{Y}{\sqrt{(1-r^2)^2 + (2\xi r)^2}}$$

But $v = \omega X$ (24)

$$a = \omega^2 X \qquad (25)$$

But, Force, $F = ma$ (26)

Mass of cracking tube and impeller, $m = \rho V$

Volume of hollow cracking tube and impeller

$$V = \pi(D-d)^2 L + LBH \qquad (27)$$

The total power considerations for the machine = Cracking power required + Power required for vibration of the whole unit = (1.55 + 0.642) kW = 2.20kW. Therefore, an electric motor of 2.25kW rating, 3hp and 1430rpm was used for this design. Since the total power consideration for this machine has been increased from 1.55kW to 2.25kW due to the inclusion of the vibration shock needed for the sorting unit, the total torsional stress on the shaft therefore will be increased by an equal proportion, according to the linear relation between Torque (T) and Power(P) given in (16) above, the total torque on the shaft becomes:

T = 2250/185.18 = 12.15Nm

Compensating for this torque increase of (12.15 – 8.376 = 3.774Nm) on the shaft amounts to an increase in the shaft sizing from a diameter of 30mm to a diameter of 40

2.2 Performance Evaluation

2.2.1 The cracking efficiency

By utilizing [21] equation for efficiency which was adopted for the dehulling efficiency for the Moringa dehulling machine by [22], the cracking efficiency for the palm nut cracker was derived as:

Cracking Efficiency

$$= \frac{\text{Mass of cracked palm nuts}}{\text{Mass of input palm nuts}} \times 100\% \qquad (28)$$

2.2.2 Throughput capacity

Throughput capacity (nuts/hour) $= \frac{Mass\ of\ palm\ nuts}{\text{Cracking time}}$ (29)

2.3 Optimization of Palm nut cracking and separating machine

An optimization model for palm nut cracking efficiency in terms of masses was developed using MATLAB software. To develop the optimization model, an objective function, constraints, and decision variables were defined as follows:

2.3.1 Objective Function

The study would maximize the cracking efficiency (C_{eff}), which represents the ratio of the mass of cracked palm kernel nuts (M_{out}) to the Mass of palm kernels fed or input into the cracking machine (M_f), and it expressed mathematically as follows:

$$\max C_{eff} = \frac{M_{out}}{M_f} \quad (30)$$

Where

M_f= Mass of palm kernels fed into the cracking machine (kg)

M_{out} = Mass of cracked palm nuts output of the machine (kg)

M_{sc} = Mass of shells separated from the cracked palm kernels (kg)

M_{fc} = Mass of fibrous material obtained from the cracking process (kg).

2.3.2 Constraints

Constraint on mass balance: The sum of the masses of the output components should equal the input mass.

$$M_f = M_{out} + M_{sc} + M_{fc} \quad (31)$$

Constraints on the individual masses:

$0.9 <= M_f <=1$

$0.88 <= M_{out} <= 0.95$

$0.1 <= M_{sc} <=0.2$

$0.04 <= M_{fc} <= 0.07$

3. Results and Discussion

3.1 Results

Table 1 presents the performance outcomes of the palm nut cracking machine, featuring a 3hp (1430rpm) electric motor in its design. The experimentation involved processing five (5) different 1kg palm kernel samples, with the resulting data documented. The cracking times range from 44.21 seconds to 50.02 seconds, reflecting the minimum and highest cracking durations. The machine broke 1kg of palm kernel in 47.58 seconds on average, yielding 0.853kg, 0.064kg, and 0.082kg of cracked, partially cracked, and uncracked palm kernels, respectively. 0.810kg of the cracked palm kernels were unbroken, whereas 0.0432kg were broken. This result suggests that the machine can crack 0.02102 kg of palm nut each second, which equates to a cracking rate of 21.02 g/s.

Table 1. Performance tests on the palm nuts cracking machine at 1430 rpm

Mass of Palm kernel nut (kg)	Cracking time (s)	Mass of uncracked nuts (kg)	Mass of partially cracked nuts (kg)	Mass of cracked nuts (kg)	Mass of unbroken kernel	Mass of broken kernel (kg)
1	46.13	0.086	0.096	0.818	0.793	0.025
1	50.02	0.057	0.060	0.883	0.841	0.042
1	48.26	0.059	0.101	0.840	0.801	0.039
1	44.21	0.080	0.085	0.835	0.781	0.054
1	49.27	0.040	0.070	0.890	0.834	0.056
Average	47.58	0.0644	0.0824	0.8532	0.810	0.0432

Table 2 likewise displays the varied cracking times for each experiment and the resulting throughput values for individual samples. The table results suggest that, at a constant speed of 1430 rpm, the smaller the cracking time, the bigger the machine's throughput, implying an inverse relationship between throughput and cracking time, as shown in Eq. 29.

A cracking efficiency, assessed using Equation 28 based on the number of fully cracked nuts in a 1kg batch, revealed an average of 0.8532kg completely cracked, a cracking efficiency of 85.32%. Similarly, unbroken and broken kernels from the cracked nuts demonstrated 81% and 4.32% efficiencies, respectively. The machine achieved a throughput capacity of 76kg/hr. Interestingly, the machine demonstrated remarkable cracking efficiency, and it is worth noting that the size of the nuts had no effect on the performance of the produced cracking machine. The machine's total production cost was N260,100.00 as shown in **Appendix A** (about USD342 at a N760/USD conversion rate). This manufacturing cost is much cheaper than that of a similar-function machine built in China, which costs USD1,300 [23].

Table 2. Cracking time and throughput of the palm nut cracking machine at 1430 rpm

Mass of Palm kernel nuts (g)	Cracking time (s)	Throughput (g/s)
1000	46.13	21.678
1000	50.02	19.992
1000	48.26	20.721
1000	44.21	22.619
1000	49.27	20.296

3.2 Optimal Performance Results

The optimal performance values of the machine were obtained by solving objective function within the constraints using Eq.30 and Eq.31, implemented in a MATLAB program code developed for the optimization model as shown in **Appendix C**. The obtained outcome reveals the optimized quantities for the cracking machine's operation: 1 kg for the mass of palm kernels fed into the machine, 0.880kg of the cracked palm nuts produced, 0.100kg for the mass of shells separated from the cracked palm kernels, 0.020kg for the mass of fibrous material obtained from the cracking process, and an 88% cracking efficiency.

3.3 Comparison of Experimental and Optimised Cracking Efficiencies

The experimental and optimised cracking efficiencies were compared and result showed in Table 3 presenting increased in cracking efficiency of up to 2.49% arising from optimizing the performance of the machine using MATLAB program.

Table 3. Comparison of Experimental and Optimised Cracking Efficiencies

S/NO	Experimental Cracking Efficiency (%)	Optimized Cracking Efficiency (%)	Increase in Efficiency (%)
1	81.80	84.21	2.41
2	88.30	89.38	1.08
3	84.00	86.10	2.10
4	83.50	85.99	2.49
5	89.00	90.00	1.00
Average	85.32	87.14	1.82

4. CONCLUSIONS

In this research, we successfully designed and developed an economically feasible machine for cracking and separating palm nuts. The process involved various stages, including design analysis, performance evaluation, and optimization using a MATLAB predictive model for the machine. According to the experimental result, the machine cracked 1kg of palm kernel in 47.58 seconds on average, yielding 0.853kg of cracked, 0.064kg of partially cracked, and 0.082kg of uncracked palm kernels, achieving a cracking efficiency of 85.32%. Among the cracked palm kernels, 0.810kg were unbroken, and 0.0432kg were broken, with efficiency of 81% and 4.32%, respectively. The machine had a throughput capacity of 76kg/hr, and the total cost of manufacture was USD342. This technology significant contributes to local technology, particularly low-income farmers and medium-sized businesses in developing nations like Nigeria. With its affordability, the machine has the potential to revolutionize palm nut cracking processes in rural areas, fostering improved productivity and efficiency. Moreover, its user-friendly design requires minimal training for operation and maintenance, making it a practical and accessible solution for enhancing palm kernel processing in resource-constrained settings.

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APPENDIX A: Costs Materials and Production

S/NO	Description	Quantity	Rate (N)	Cost (N)
1	3hp Electric motor	1	155,000	155,000.00
2	Square pipe	2	2,800	5,600.00
3	Bearings	2	1,500	3,000.00
4	Pulley	2	3,000	6,000.00
5	Belt	1	1,500	1,500.00
6	Shaft	1	6,000	6,000.00
7	Metal sheet	1	20,000	20,000.00
8	Screws	4	1,000	4,000.00
9	Mesh	2	1,500	3,000.00
10	Fabrication	-	45,000	45,000.00
11	Miscellaneous	-	3,000	3,000.00
12	Paint	1	2,000	2,000.00
13	Transportation	-	6,000	6,000.00
	Total			**260,100.00**

APPENDIX B: Optimal Iteration

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Iter   F-count        f(x)        Feasibility    First-order optimality    Norm of step
   0       5    -9.321053e-01     1.405e-01          5.000e-02
   1      11    -9.124591e-01     8.416e-02            7.201e-02            3.379e-02
   2      16    -8.869734e-01     1.832e-02            7.328e-02            3.937e-02
   3      21    -8.839258e-01     4.200e-03            1.450e-02            1.119e-02
   4      26    -8.802239e-01     6.298e-04            1.484e-02            3.850e-03
   5      32    -8.801819e-01     4.206e-04            8.721e-03            1.695e-04
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6	38	-8.801101e-01	2.355e-04	4.508e-03	9.723e-05
7	44	-8.800561e-01	1.191e-04	2.432e-03	5.820e-05
8	50	-8.800282e-01	6.007e-05	1.272e-03	2.952e-05
9	56	-8.800142e-01	3.023e-05	1.012e-03	1.492e-05
10	62	-8.800071e-01	1.520e-05	6.060e-04	7.517e-06
11	68	-8.800036e-01	7.640e-06	4.029e-04	3.778e-06
12	74	-8.800018e-01	3.841e-06	3.015e-04	1.899e-06
13	80	-8.800009e-01	1.930e-06	1.707e-04	9.555e-07
14	86	-8.800005e-01	9.701e-07	1.054e-04	4.801e-07
15	92	-8.800002e-01	4.875e-07	7.268e-05	2.413e-07
16	98	-8.800001e-01	2.450e-07	4.034e-05	1.213e-07
17	104	-8.800001e-01	1.231e-07	2.417e-05	6.094e-08
18	110	-8.800000e-01	6.186e-08	1.608e-05	3.062e-08
19	116	-8.800000e-01	3.108e-08	1.204e-05	1.539e-08
20	122	-8.800000e-01	1.562e-08	6.821e-06	7.732e-09
21	128	-8.800000e-01	7.849e-09	4.211e-06	3.886e-09
22	134	-8.800000e-01	3.944e-09	2.905e-06	1.952e-09
23	140	-8.800000e-01	1.982e-09	1.613e-06	9.811e-10
24	146	-8.800000e-01	9.959e-10	9.663e-07	4.930e-10

APPENDIX C: MATLAB Code for Optimal Performance of the Palm Nut Cracking and Separating Machine

```
% Define the objective function
objective = @(x) -x(2) / x(1); % Cracking efficiency: maximize M_q / M_fr


% Define the constraints
lb = [0.9, 0.88, 0.1, 0.02]; % Lower bounds
ub = [1, 0.89, 0.2, 0.07];   % Upper bounds
A = [];                       % No linear inequality constraints
b = [];                       % No linear inequality constraints
Aeq = [1, -1, -1, -1];        % Mass balance constraint coefficients
beq = 0;                      % Mass balance constraint RHS


% Perform optimization
x0 = [0.95, 0.94, 0.15, 0.055]; % Initial guess
options = optimoptions('fmincon', 'Display', 'iter');
[x_opt, fval] = fmincon(objective, x0, A, b, Aeq, beq, lb, ub, [], options);
```

```
% Extract the optimized masses and cracking efficiency
M_fr_opt = x_opt(1);
M_q_opt = x_opt(2);
M_sc_opt = x_opt(3);
M_fc_opt = x_opt(4);
Ceff_opt = -fval;

% Display the optimized results
fprintf('Optimized Values:\n');
fprintf('M_fr = %.3f kg\n', M_fr_opt);
fprintf('M_q = %.3f kg\n', M_q_opt);
fprintf('M_sc = %.3f kg\n', M_sc_opt);
fprintf('M_fc = %.3f kg\n', M_fc_opt);
fprintf('Cracking Efficiency (Ceff) = %.3f\n', Ceff_opt);
```

APPENDIX D: Pictures of Parts of the fabricated Palm Kernel Cracking and Separation Machine

(a) Cracking drum on main frame

(b) Feed-in unit (hopper)

(c) Cracking hammer shaft

(d) Electric motor connected to drum