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# Performance Evaluation and Optimization of a Palm Kernel Cracker – A Taguchi-Grey Relational Analysis Approach

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**ABSTRACT**

The palm kernel cracking machine plays an important role in the palm oil and kernel oil processing industries for removing kernels from the outer shells. The parameters of the machine operation are required to be optimized to achieve the best machine efficiency. This study optimizes a palm kernel cracker using the Taguchi-Grey relational analysis approach. A $L_9$ orthogonal array was used for the experimental design using two factors at three levels (speed – 1000, 1200, and 1400 rpm; weight – 2, 4, and 6 kg). Analysis of variance and regression analysis were done. The results revealed that the machine's efficiency greatly influences the rotation speed compared to the nuts' weight. The throughput capacity was higher at higher weight and lower cracking time. For most of the responses, the weight of the palm kernel nuts was ranked more important than the machine's rotation speed. For the optimization, optimum cracking efficiency was at 1000 rpm speed and 4 kg weight; optimum throughput capacity and optimum labour requirement were obtained at 1000 rpm speed and 6 kg weight, respectively. Mathematical models were developed for all responses using the input parameters. The experimental values and the predicted optimum results were determined to be close based on the processing conditions. Also, the mathematical models suitably predicted the performance of the developed palm kernel cracking machine.

## 1. INTRODUCTION

Oil palm fruits are edible seeds and are usually referred to as palm kernels. Two different types of oils are obtainable from the oil palm fruits. Palm oil is extracted from the exterior part of the fruit, while palm kernel oil is derived from the kernels [1, 2]. The oil palm is one of the richest oil plants with adequate nutrients present in it [3]. Several products are obtainable from palm kernels through various processes. For instance, the palatable seed is used for the oil palm organic product. After the oil is extracted from the kernel, the leftover pulp is turned into palm kernel cake with high protein nutrients for livestock feeding. It can also be converted by boiling in boilers for power generation [2, 4].

The process of palm kernel seed removal from palm kernel shell is an activity that requires cracking the palm kernel shell (PKS). The economic importance of palm kernel that calls for the cracking of the PKS is due to its numerous applications in food, confectionery, traditional medicine, and cosmetic industries [5-7]. This economic importance leads to its high demand in the global markets and the need to effectively extract the kernel from the shell. Hence, the palm kernel shell must be sundried for sufficient shrinkage of the kernel from the shell and the avoidance of kernel breakage before being cracked either manually or mechanically [1, 8]. The removal of the kernel from PKS is still being done manually in some rural areas, by breaking the PKS with a stone before sorting the kernel and the remaining PKS by hand. The manual method is time-consuming with a series of drudgeries linked to the process. This process is economically not rewarding for rural farmers as the bulk of the processing cost is paid to the workers manually cracking the kernel. Meanwhile, several machines have been designed for the removal of the kernel from the PKS mechanically [1, 8-10]. These cracking machines have been developed and reported with different efficiencies in literature.

A palm kernel shelling and sorting machine was developed by Ismail et al. [11]. The machine was evaluated to have 70% whole kernel recovery, 90% shelling and sorting efficiency, and 59 kg/h throughput. In a related study by Adejuyigbe et al.

[3], the efficiency of the developed improved palm kernel shelling and sorting machine was 98% and the processing rate was 95 nuts/s. The performance evaluation of two different palm kernel cracking machines developed by Oyebanji et al. [12] was determined. One of the palm kernel crackers uses a vertical centrifugal mechanism while the second cracker uses a centrifugal impact approach. The efficiencies of the machines were 71.3% (vertical centrifugal mechanism) and 50.38% (centrifugal impact mechanism). Alade et al. [5] modified an existing palm nut cracker due to a high level of mechanical kernel damage. After the modification, the cracking efficiency of the machine was between 86.10 and 97.27%, average kernel breakage was 4.59%, and whole kernels percentage ranged from 94.85 to 95.97%.

Ibikunle et al. [1] developed and evaluated the performance of a palm nut-cracking machine. The average cracking efficiency and throughput of the machine at two speeds of rotation of 1200 and 1400 rpm is 74.2% and 75.6 kg/h. The cracking time reduces, and throughput increases with increased shaft speed. The obtained efficiency is lower compared to other studies earlier reported. Some parts were required to be modified in the machine to achieve improved efficiency. Also, optimization of the process parameters is not considered in the study. Olaoye and Adekanye [13] studied the properties that influenced the cracking and separation of palm nuts in a mechanical cracker with a separator. The process was not optimized. Also, John et al. [14] developed a palm kernel cracking and separation machine without optimizing the machine.

Performance evaluation and optimization of the process parameters of developed machines are germane to the optimal setting of the process parameters. A response surface methodology (RSM) was used by Komolafe et al. [15] during the optimization of a moringa depodding machine. In the same vein, the optimization of the palm kernel cracking machine has been done [16, 17]. In the study of Omoruyi and Ugwu [16], the optimization was done using statistical analysis of the Analysis of Variance (ANOVA). The input parameters include moisture content and rotor speed, while the output parameters are cracking efficiency, percentage losses, recovery rate, mass flow rate, and mechanical damage. The optimal setting of the cracking efficiency (98.18%) and mass flow rate (22.45 kg/min) for the Dura palm kernel shell and cracking efficiency (98.15%) and mass flow rate (23.87 kg/min) for the Tenera palm kernel shell were obtained at 9% moisture content and 2,600 rpm rotor speed. Sam et al. [17] developed models, validated, and optimized the performance parameter for a developed palm nut-cracking machine using mixed palm nuts variety. The input parameters are the cracking speed (five levels), moisture content (six levels), and feed rate (five levels). The design of the experiment used was a full factorial design while the model to predict the whole kernel recovery was done using the Buckingham Pi theorem concept. The study showed that the optimum combination for the optimization of the process parameters was 580.41 kg/h (feed rate), 151.43 kg/h (throughput capacity), 12.51 m/s (nut speed), 33.78 m/s (peripheral velocity), 1935 rpm (cracking speed), and 16.69% wet basis (moisture content).

The performance evaluation and optimization of palm kernel cracking machines using the Taguchi-Grey relational analysis approach and statistical analysis to the authors' best of knowledge have not been reported. Hence, the process parameters of the modified machine developed by Ibikunle et al. [1] are required to be optimized and mathematical models developed. The effects of the input parameters on the output parameters of the machine as well as the interactive effects of the input parameters on the output parameters of the machine for the determination of their optimal settings. Therefore, this study is focused on the performance evaluation and optimization of a palm kernel nuts-cracking machine via the Taguchi-Grey relational analysis and regression analysis.

## 2. MATERIALS AND METHODS

### 2.1 Collection and preparation of samples

The palm kernel used in this study was obtained from one of the palm oil processing areas in Omu-Aran and its environs. It was sorted to remove stones, sticks, and other stuff that might affect the machine's performance. The palm kernels were sundried for 3 days (7 h/day) to reduce the inherent moisture and easy cracking of the palm kernel. The initial moisture content of the palm kernel nuts was obtained to be 10.48% (wet basis) using the AOAC method [18], which was used in the study of Komolafe et al. [15]. The palm kernels were grouped into three and further subdivided into three groups with two replicates for the experimental study.

### 2.2 Description and operation of the machine

The machine is made up of the following components which include the feed-in unit, also known as the hopper, the cracking unit, also known as the drum, the driving unit, which is made up of an electric motor, pulley, and V-belt, and the driven unit, which consists of a rotating shaft bearing the cracking unit. Hammers are propelled by a prime mover's V-belt.

The stand and supporting structure are made out of angle iron that has a gauge of 50 mm by 50 mm by 6 mm. The hopper is made of mild steel and has a thickness of 3 mm. It holds about 10.8 kg of palm nuts. It has a capacity of 0.018 $m^3$. The cracking drum is made of a length of 50 mm, another length of 25 mm at the other end for a length of 100 mm, and a length of 30 mm in the center, where the hammers are attached for a length of 150 mm. The hammers are made of mild steel which is 8 mm thick and measures 130 mm in length, 50 mm in width, and 3 mm in thickness. The drive unit's electric motor has a 1 hp rating and runs at 1400 rpm and 50 Hz. The 12 mm broad. 9 mm thick, and 480 mm long V-belt that the pulley, which has an 80 mm diameter, is attached to. The pulley connected to the rotating shaft is 175 mm in diameter.

When the palm kernel nuts are poured into the hopper, they move down into the cracking chamber with the help of gravity aided by the vibration of the prime mover. The hammer impacts force on the palm kernel nuts which are then thrown against the walls of the cracking drum. The impact of the hammer on the palm kernel nuts leads to the breaking of the nuts and its shelling which is achieved as a result of centrifugal action. The broken nuts and the shells are then forced out of the cracking chamber into the outlet where they are collected.

The orthographic projection and isometric view of the machine is displayed in Figure 1. Figure 2 presents the exploded view showing the different components of the machine, and pictorial view of the machine showing external parts and cracking hammer are shown in Figures 3 and 4, respectively.

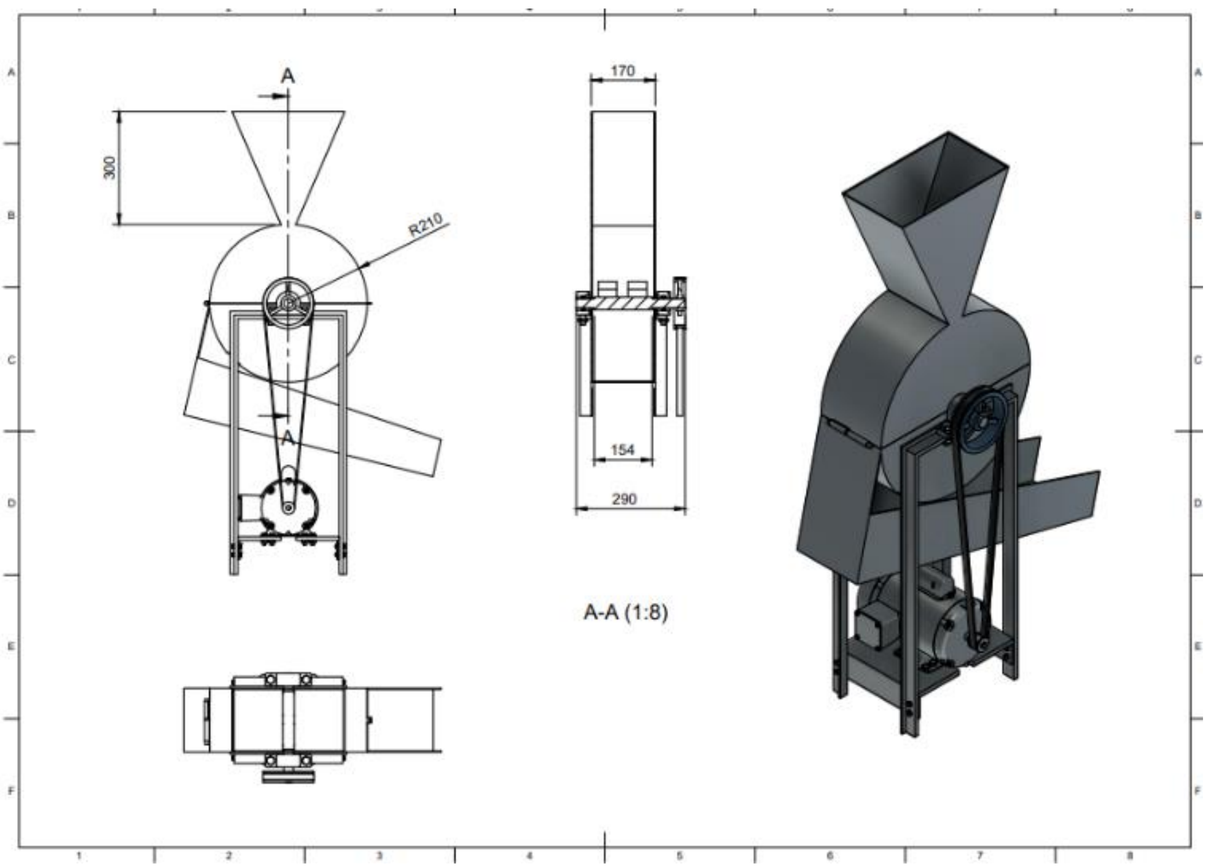



**Figure 1.** Orthographic and isometric projections of the machine

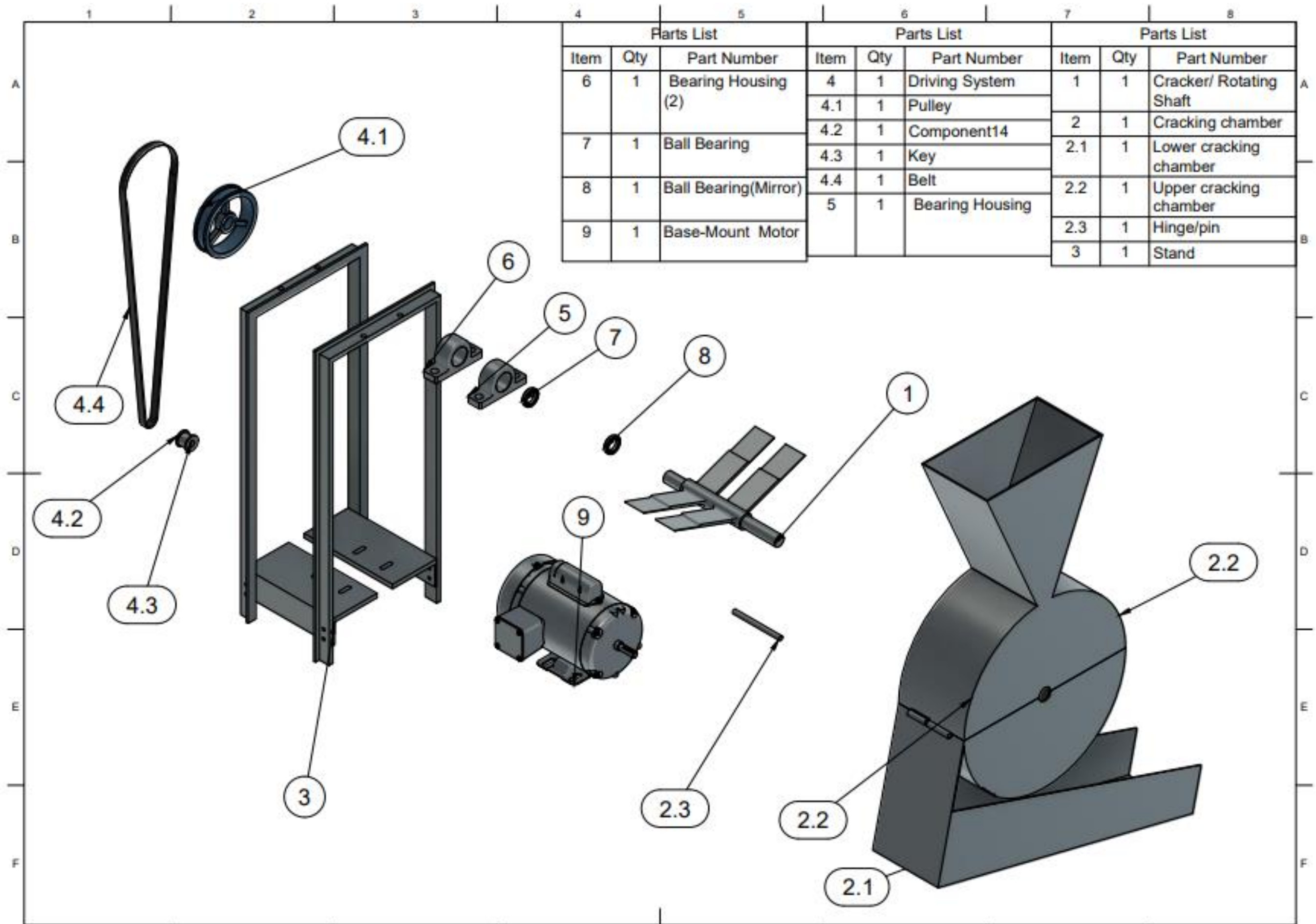



**Figure 2.** Exploded view of the machine

### 2.3 Experimental design

Two input factors (speed of rotation and palm kernel weight) are used in this study. Three levels were selected for each factor. The speed of rotation has levels 1000, 1200, and 1400 rpm, while the weight of palm kernel has levels 2, 4, and 6 kg. Taguchi technique was utilized to optimize the responses. As a result of the two process parameters with three different levels, an $L_9$ orthogonal array was chosen. Taguchi method requires the output response to be transformed to signal-to-noise (S/N) ratios; hence, the output responses were required for minimization or maximization. Therefore, the performance characteristics selected for the determination of the S/N ratio are both smaller-the-better and larger–the–better using Eqs. (1) and (2), respectively.

$$S/N_s = -10log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

$$S/N_l = -10log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \quad (2)$$

where, $n$ and $y_i$ are replication number for each test and $i_{th}$ value of the performance characteristics, respectively.

The input parameters were the rotational speeds of the cracking shaft (1000, 1200, and 1400 rpm) and the palm kernel nuts weight (2, 4, and 6 kg), as displayed in Table 1.

**Table 1.** Palm kernel nut cracker at various processing conditions

| Speed of Rotation (rpm) | Mass of Palm Kernel Nut (kg) |
|---|---|
| 1000 | 2 |
| 1200 | 4 |
| 1400 | 6 |

### 2.4 Experimental procedures

Due to the employment of several pulleys, the sorted palm kernel nuts were fed into the cracking machine at various weights and rotational speeds. The apparatus employed includes a hopper, a cracking unit (cracking shafts and hammers), an electric motor, and an outlet as displayed in Figures 3 and 4. The machine was driven by a 1 hp electric motor.


**Figure 3.** Pictorial view of the machine showing external parts [1]


**Figure 4.** Pictorial view showing the cracking hammer [1]

### 2.5 Performance evaluation of the machine

At various machine speeds, the machine was tested using various weights of palm kernel nuts. The weight was obtained using a digital weighing scale. The cracked weight, uncracked weight, and weight of partially cracked palm kernel nut as well as time of operation were recorded using a stopwatch. The average value after triplicate experiments was used. The recorded values were then used in the evaluation of the cracking efficiency and throughput efficiency using Eqs. (3) and (4), respectively.

Table 1 shows the performance evaluation processing conditions for the developed palm nuts cracking machine, with speeds of 1000, 1200, and 1400 rpm, respectively. The labour requirement was also determined using Eq. (5).

$$\text{Cracking Efficiency (\%)} = \frac{\text{Mass of cracked palm kernel nuts}}{\text{Total mass of input palm kernel nuts}} \times 100\% \quad (3)$$

$$\text{Throughput Capacity}\left(\frac{\text{kg}}{\text{s}}\right) = \frac{\text{Mass of input palm kernel nuts}}{\text{Cracking Time}} \quad (4)$$

$$\text{Labour Requirement} = \frac{1}{\text{Throughput capacity}} \quad (5)$$

### 2.6 Machine performance optimization

The Taguchi-Grey relational analysis (Taguchi-GRA) of Minitab 19 was employed for the experimental design and analyses. Also, the $L_9$ orthogonal array with two (2) factors and three (3) levels was applied to generate the required experimental runs in the study as displayed in Table 2. ANOVA and regression analysis were done for model equations generation which depicts the different performances of the developed machine.

GRA is used to initially normalize the experimental results usually between 0 and 1. The larger-the-better performance criterion was chosen for all the responses.

The efficiencies and throughput capacity of the palm nuts cracker with the input parameters were evaluated to obtain the performance models. According to Komolafe et al. [15] and Falade and Aremu [19], an analysis of variance at a p-value ($p<0.05$) was conducted using the various performances to determine the significance and interactions of the developed models with the performance responses. The desired outputs (throughput capacity and cracking efficiency) were maximized while the undesirable responses (labour required) were minimized through additional analysis of the variable optimization. Other responses from the experiment were optimized.

**Table 2.** Experimental design using $L_9$ orthogonal array

| Run Order | SoR (rpm) | Weight (kg) |
|---|---|---|
| 1 | 1000 | 2 |
| 2 | 1000 | 4 |
| 3 | 1000 | 6 |
| 4 | 1200 | 2 |
| 5 | 1200 | 4 |
| 6 | 1200 | 6 |
| 7 | 1400 | 2 |
| 8 | 1400 | 4 |
| 9 | 1400 | 6 |

*SoR – Speed of rotation

## 2.7 ANOVA

As a veritable statistical tool, ANOVA is used to determine the interactions and contribution ratio of all the input parameters. In this experimental design, ANOVA was not only adopted to validate Taguchi's results but also to analyze the effects of the speed of rotation (SoR) and weight of palm nut on the cracking time (CT), cracked nut (CN), partially cracked nut (PCN), uncracked nut (UCN), cracking efficiency (CE), throughput capacity (TC), and labour required (LR).

## 2.8 Confirmation test

Having established the optimum values of CT, CN, PCN, UCN, CE, TC, and LR from the S/N ratio plots of Taguchi experiments using Eqs. (6)-(12), then confirmation tests were carried out to ascertain and validate the optimum values obtained [20].

$$\mathrm{CT}(\mathrm{A_1B_1}) = \mathrm{M_{CT}} + (\mathrm{M_{A1}} - \mathrm{M_{CT}}) + (\mathrm{M_{B1}} - \mathrm{M_{CT}}) \quad (6)$$

$$\mathrm{CN}(\mathrm{A_3B_3}) = \mathrm{M_{CN}} + (\mathrm{M_{A3}} - \mathrm{M_{CN}}) + (\mathrm{M_{B3}} - \mathrm{M_{CN}}) \quad (7)$$

$$\mathrm{PCN}(\mathrm{A_3B_1}) = \mathrm{M_{PCN}} + (\mathrm{M_{A3}} - \mathrm{M_{PCN}}) + (\mathrm{M_{B1}} - \mathrm{M_{PCN}}) \quad (8)$$

$$\mathrm{UCN}(\mathrm{A_1B_1}) = \mathrm{M_{UCN}} + (\mathrm{M_{A1}} - \mathrm{M_{UCN}}) + (\mathrm{M_{B1}} - \mathrm{M_{UCN}}) \quad (9)$$

$$\mathrm{CE}(\mathrm{A_1B_2}) = \mathrm{M_{CE}} + (\mathrm{M_{A1}} - \mathrm{M_{CE}}) + (\mathrm{M_{B2}} - \mathrm{M_{CE}}) \quad (10)$$

$$\mathrm{TC}(\mathrm{A_1B_3}) = \mathrm{M_{TC}} + (\mathrm{M_{A1}} - \mathrm{M_{TC}}) + (\mathrm{M_{B3}} - \mathrm{M_{TC}}) \quad (11)$$

$$\mathrm{LR}(\mathrm{A_1B_3}) = \mathrm{M_{LR}} + (\mathrm{M_{A1}} - \mathrm{M}_{LR}) + (\mathrm{M_{B3}} - \mathrm{M_{LR}}) \quad (12)$$

where, the values of the optimum level of CT, CN, PCN, UCN, CE, TC, and LR are respectively represented as ($A_1B_1$), ($A_3B_3$), ($A_3B_1$), ($A_1B_1$), ($A_1B_2$), ($A_1B_3$), and ($A_1B_3$); while $M_{CT}$, $M_{CN}$, $M_{PCN}$, $M_{UCN}$, $M_{CE}$, $M_{TC}$, and $M_{LR}$ are the average of all the respective optimum response obtained from the experimental study.

The conformity of the predicted optimum values to the actual experimental values is determined by evaluating the confidence interval (CI) using Eqs. (13) and (14).

$$CI = \sqrt{F_\alpha(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad (13)$$

$$n_{eff} = \frac{N}{1 + T_{dof}} \quad (14)$$

where, $F_\alpha(1, f_e)$ = $F$ ratio at a 95% confidence, $f_e$ = degrees-of-freedom of error, $n_{eff}$ = effective number of replications, $\alpha$ = significance level, $V_e$ = variance's error, $N$ = total number of experiments, $R$ = number of confirmation experiments' replication, and $T_{dof}$ = total main parameters degrees of freedom.

# 3. RESULTS AND DISCUSSION

## 3.1 Taguchi-Grey relational analysis of the performance

Signal-to-noise ratio (S/N) analysis of the responses

The output responses of the input factors and the S/N are presented in Table 3. Different responses were obtained based on experimental runs. Table 4 displays the signal-to-noise ratio for each output response based on ranking of the input factors.

Taguchi analysis of CT

The mean S/N ratios and the ranking of the importance of input parameters on the CT are germane in the response in the analysis of the CT. The main effects plot of each input factor on the CT of the machine is presented in Figure 1. From the figure, the input factors to attain the optimal values for the CT response are determined as the speed of rotation = 1000 rpm and weight = 2 kg (Figure 5). This implies that the best cracking time is achieved when the machine is operated at 1000 rpm speed using 2 kg weight of the palm nuts. The contribution of the weight used is found to be significant.

Taguchi analysis of CN

The main effects plot in Figure 6 shows that the larger-the-better condition is required to achieve an optimum value for CN. Figure 6 shows that the CN response is determined as the speed of rotation = 1000 rpm and weight = 6 kg. The nuts would be properly cracked with the 6 kg weight of the palm nuts and at 1000 rpm speed.

Taguchi analysis of PCN and UCN

The smaller-the-better condition is utilized for the responses (PCN and UCN). For the PCN, the best combinations to obtain the optimum PCN are speed of rotation = 1400 rpm and weight = 2 kg (Figure 7). However, for the UCN, the best combinations for obtaining the optimum UCN are 1000 rpm speed of rotation and 2 kg weight of the palm nuts (Figure 8). The main effects plots for the PCN and UCN are displayed in Figures 7 and 8, respectively. To achieve better effectiveness of the machine, it is required that the palm nuts are cracked with reduced partially cracked and uncracked nuts. Hence, the speed of rotation during cracking should be optimized for the machine's effectiveness and efficiency.

Taguchi analysis of CE and TC

The larger-the-better condition was considered for the CE and TC responses. The CE and TC are germane parameters in considering the effectiveness of a developed machine [15]. In this study, the CE response is best determined at 1000 rpm speed of rotation and 4 kg weight of the palm nuts. This observation can be seen on the main effects plot of CE as displayed in Figure 9. This implies that the best machine operational efficiency is achievable at 1000 rpm speed and 4 kg weight. For the CE, the speed of rotation contributed more to the response than the weight of the palm nuts. This is the essence of the optimization of the rotation speed of the machine's shaft. Figure 10 displays the main effects plot for the TC. The TC response is best evaluated at speed of rotation = 1000 rpm and weight = 6 kg. TC is majorly dependent on the cracking time and weight of the palm nuts [1]. Lower cracking time as well as higher weight of palm nuts leads to higher TC of the machine.

**Table 3.** Input parameters (speed & weight) vs. output parameters: CT, CN, PCN, UCN, CE, LR

| Input Parameters | | Output Parameters | | | | | | | Signal-to-Noise Ratios | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Speed | Weight | CT | CN | PCN | UCN | CE | TC | LR | SNRA1 | SNRA2 | SNRA3 | SNRA4 | SNRA5 | SNRA6 | SNRA7 |
| 1000 | 2 | 13.465 | 1.265 | 0.610 | 0.125 | 93.750 | 0.1485 | 6.7325 | -22.5841 | 2.041811 | 4.293403 | 18.0618 | 39.43943 | -16.5655 | -16.5635 |
| 1000 | 4 | 31.510 | 2.665 | 1.085 | 0.250 | 93.750 | 0.1283 | 7.7916 | -29.9690 | 8.513944 | -0.70859 | 12.0412 | 39.43943 | -17.8355 | -17.8325 |
| 1000 | 6 | 44.215 | 4.230 | 1.385 | 0.385 | 93.580 | 0.1357 | 7.3689 | -32.9114 | 12.52681 | -2.82900 | 8.290785 | 39.42366 | -17.3484 | -17.3481 |
| 1200 | 2 | 15.535 | 1.230 | 0.640 | 0.130 | 93.500 | 0.1289 | 7.7586 | -23.8262 | 1.798102 | 3.876401 | 17.72113 | 39.41623 | -17.7949 | -17.7957 |
| 1200 | 4 | 32.660 | 2.665 | 1.080 | 0.255 | 93.625 | 0.1225 | 8.1650 | -30.2803 | 8.513944 | -0.66848 | 11.8692 | 39.42784 | -18.2373 | -18.2391 |
| 1200 | 6 | 43.160 | 3.895 | 1.630 | 0.475 | 92.080 | 0.1390 | 7.1924 | -32.7016 | 11.81015 | -4.24375 | 6.466128 | 39.28331 | -17.1397 | -17.1375 |
| 1400 | 2 | 18.665 | 1.305 | 0.555 | 0.140 | 93.000 | 0.1072 | 9.3322 | -25.4206 | 2.31221 | 5.11414 | 17.07744 | 39.36966 | -19.4042 | -19.3997 |
| 1400 | 4 | 27.400 | 2.760 | 0.965 | 0.275 | 93.125 | 0.1460 | 6.8498 | -28.755 | 8.818182 | 0.309454 | 11.21335 | 39.38133 | -16.7129 | -16.7136 |
| 1400 | 6 | 39.985 | 3.955 | 1.575 | 0.470 | 92.167 | 0.1503 | 6.6554 | -32.0379 | 11.94293 | -3.94561 | 6.558043 | 39.29148 | -16.4608 | -16.4635 |

CT: Cracking Time, CN: Cracked Nut, PCN: Partially Cracked Nut, UN: Uncracked Nut, CE: Cracked Efficiency, LR: Labour Requirement, GRG: Grey Relational Grade

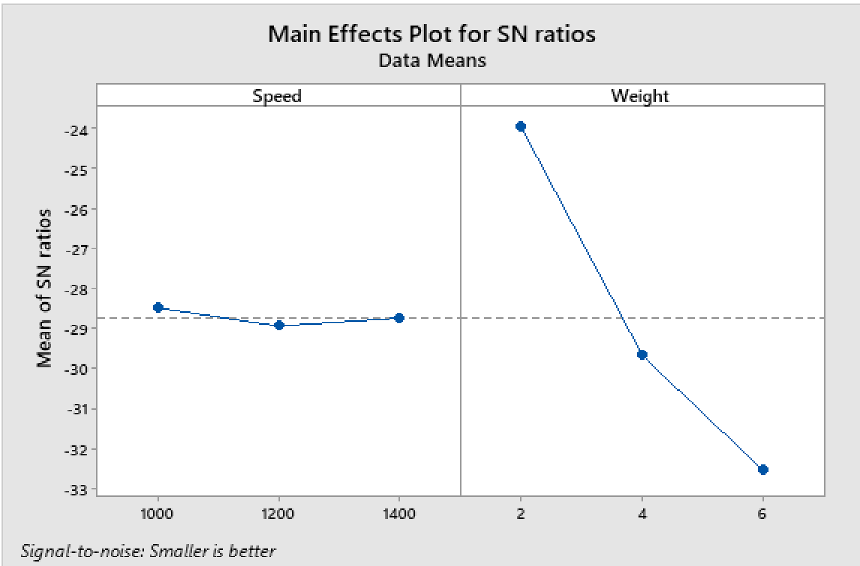



**Figure 5.** Taguchi analysis of main effects plots for CT versus speed and weight

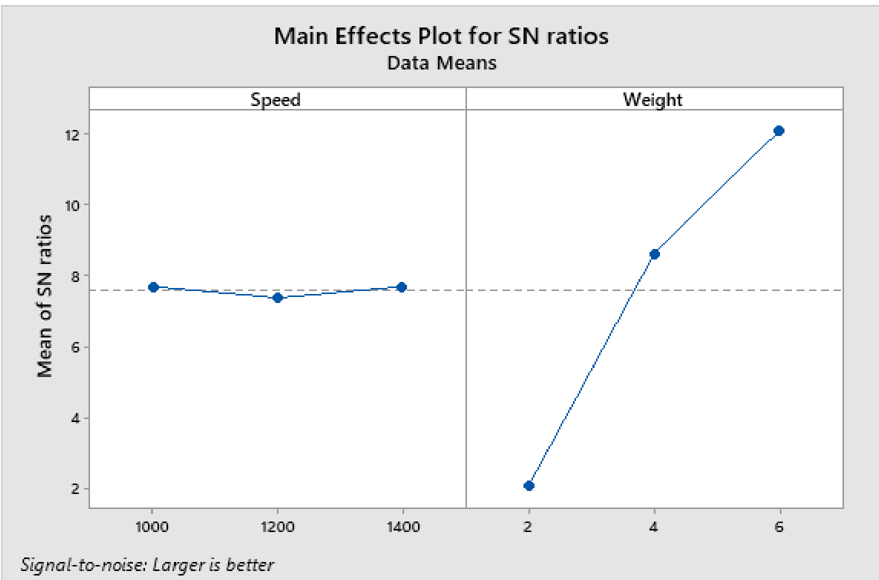



**Figure 6.** Taguchi analysis of main effects plots for CN versus speed and weight

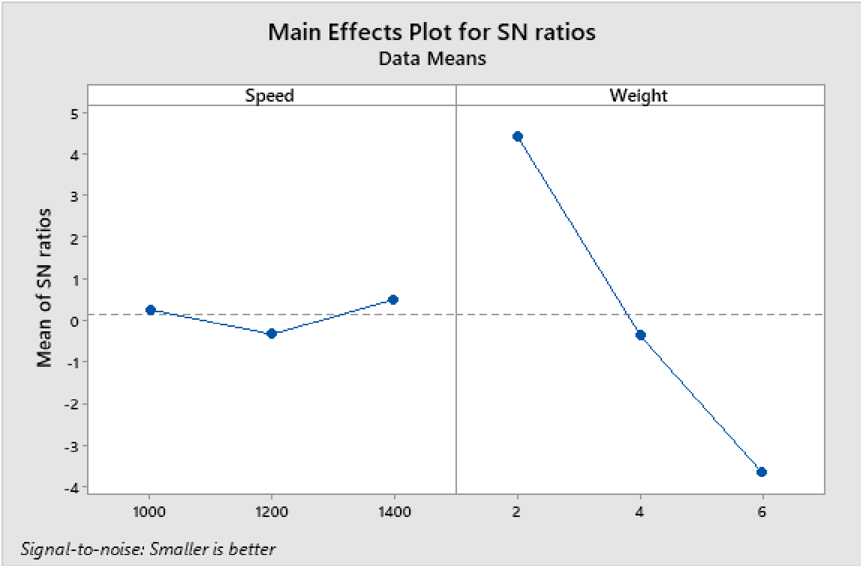



**Figure 7.** Taguchi analysis of main effects plots for PCN versus speed and weight

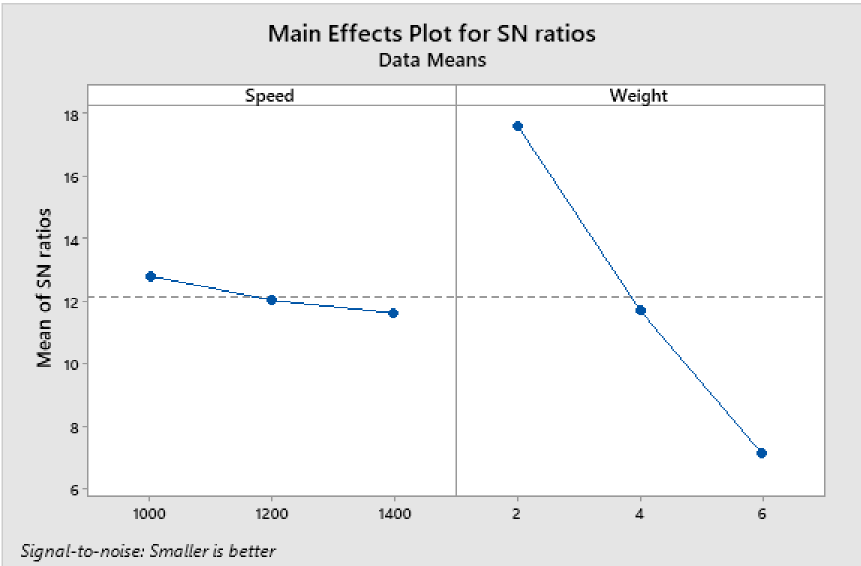



**Figure 8.** Taguchi analysis of main effects plots for UCN versus speed and weight

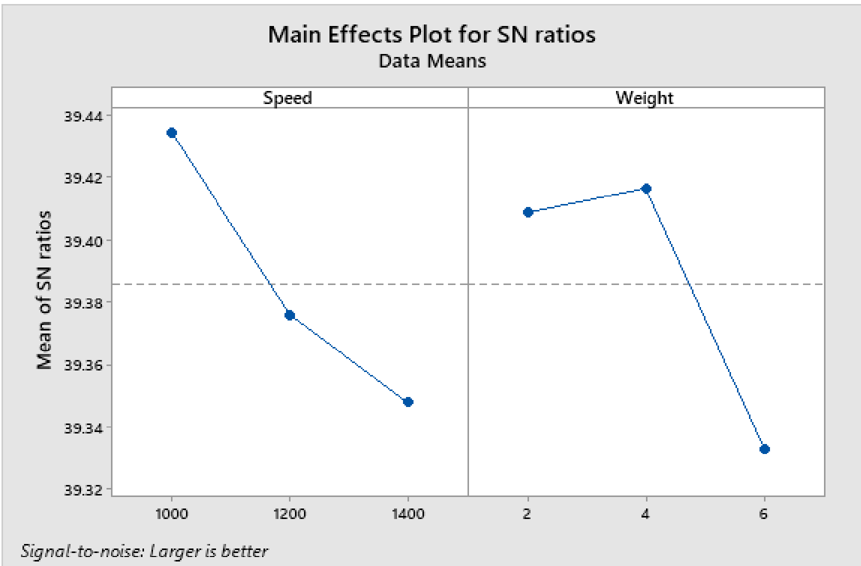



**Figure 9.** Taguchi analysis of main effects plots for CE versus speed and weight

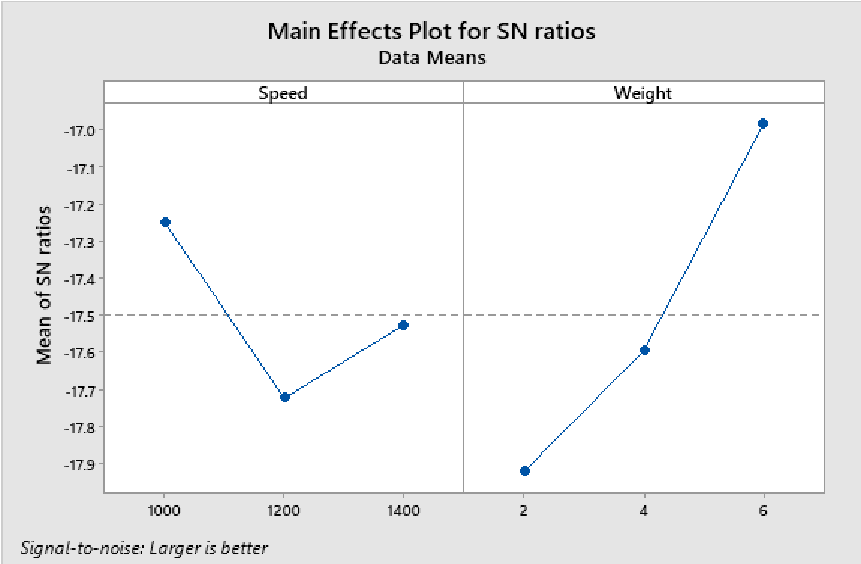



**Figure 10.** Taguchi analysis of main effects plots for TC versus speed and weight


**Figure 11.** Taguchi analysis of main effects plots for LR versus speed and weight

<u>Taguchi analysis of Labour requirement (LR)</u>

LR is the reciprocal of throughput capacity [15]. This implies that LR is also dependent on the weight of the palm nuts and the cracking time. The main effects plot of LR is displayed in Figure 11. The smaller-the-better condition was used in this analysis. The best conditions to obtain the optimum response (LR) are at speed of rotation = 1000 rpm and weight = 6 kg. The ranking of the variable factors shows that the weight is the most significant parameter that could influence the LR. It is notable to state that the increased speed of rotation decreased LR. This finding is in tandem with the studies of Komolafe et al. [15] on moringa dehuller and Okonkwo et al. [21] on locust bean dehuller, where LR reduction was reported with increased speed of rotation.

### 3.2 ANOVA of the responses

Table 5 displays the ANOVA of the responses. The weight of the nuts was observed to be the major input factor on the cracking time with a contribution of 96.48%. the contribution ratio is an indication that the ranking of the importance of the process parameters on the CT of the machine was weight > speed. This is also similar to the ranking obtained via the main effects plot. The p-value (0.001) of the weight was significant; hence, weight has a significant effect on the CT.

Similar observations obtained for CT are obtained for CN, PCN, and UCN. The contribution ratios for the weight are higher than that of the speed of rotation. The contribution ratios and p-values for the weight for each response are CN (99.37%, 0.000), PCN (96.57%, 0.001), and UCN (96.35%, 0.000). This makes the weight a more considered factor influencing the responses since the p-values are below 0.05 significant level. The contribution ratios of the speed are very low based on the analysis done.

However, for CE, TC, and LR, the contribution ratios of the speed and weight are CE (39.83%, 42.97%), TC (5.25%, 18.40%), and LR (4.74%, 19.93%), respectively. Although, the ranking of the importance parameter for the response was weight > speed.

**Table 4.** Response table for signal-to-noise ratios for the responses

| CT (Smaller is better) | | | CE (Larger is better) | | |
|---|---|---|---|---|---|
| Level | Speed | Weight | Level | Speed | Weight |
| 1 | -28.49 | -23.94 | 1 | 39.43 | 39.41 |
| 2 | -28.94 | -29.67 | 2 | 39.38 | 39.42 |
| 3 | -28.74 | -32.55 | 3 | 39.35 | 39.33 |
| Delta | 0.45 | 8.61 | Delta | 0.09 | 0.08 |
| Rank | 2 | 1 | Rank | 1 | 2 |
| **CN (Larger is better)** | | | **TC (Larger is better)** | | |
| Level | Speed | Weight | Level | Speed | Weight |
| 1 | 7.694 | 2.051 | 1 | -17.25 | -17.92 |
| 2 | 7.374 | 8.615 | 2 | -17.72 | -17.60 |
| 3 | 7.691 | 12.093 | 3 | -17.53 | -16.98 |
| Delta | 0.32 | 10.043 | Delta | 0.47 | 0.94 |
| Rank | 2 | 1 | Rank | 2 | 1 |
| **PCN (Smaller is better)** | | | **LR (Smaller is better)** | | |
| Level | Speed | Weight | Level | Speed | Weight |
| 1 | 0.2519 | 4.428 | 1 | -17.25 | -17.92 |
| 2 | -0.3453 | -0.3559 | 2 | -17.72 | -17.60 |
| 3 | 0.4927 | -3.6728 | 3 | -17.53 | -16.98 |
| Delta | 0.8379 | 8.1008 | Delta | 0.48 | 0.94 |
| Rank | 2 | 1 | Rank | 2 | 1 |
| **UCN (Smaller is better)** | | | | | |
| Level | Speed | Weight | | | |
| 1 | 12.798 | 17.62 | | | |
| 2 | 12.019 | 11.708 | | | |
| 3 | 11.616 | 7.105 | | | |
| Delta | 1.182 | 10.515 | | | |
| Rank | 2 | 1 | | | |

Table 6 displays the R-sq. and Adjusted R-sq. for each response, which confirm the fitness of regression model in Eqs. (15) to (21).

Regression Equation

The ANOVA was used to generate a general linear model (Regression Equation) for all the responses using the input parameters. The regression equations (mathematical models) are displayed from Eqs. (15) to (21) for each response, respectively.

$$CT = 29.622 + 0.11S_1 + 0.83S_2 - 0.94S_3 - 13.73W_1 + 0.9W_2 + 12.83W_3 \quad (15)$$

$$CN = 2.6633 + 0.0567S_1 - 0.0667S_2 + 0.01S_3 - 1.3967W_1 + 0.0333W_2 + 1.3633W_3 \quad (16)$$

$$PCN = 1.0583 - 0.0317S_1 + 0.0583S_2 - 0.0267S_3 - 0.4567W_1 - 0.015W_2 + 0.4717W_3 \quad (17)$$

$$UCN = 0.27833 - 0.025S_1 + 0.0083S_2 + 0.0167S_3 - 0.1467W_1 - 0.0183W_2 + 0.165W_3 \quad (18)$$

$$CE = 93.175 + 0.518S_1 - 0.107S_2 - 0.411S_3 + 0.241W_1 + 0.325W_2 - 0.566W_3 \quad (19)$$

$$TC = 0.13403 + 0.00347S_1 - 0.0039S_2 + 0.00043S_3 - 0.00587W_1 - 0.00177W_2 + 0.00763W_3 \quad (20)$$

$$LR = 7.538 - 0.241S_1 + 0.167S_2 + 0.074S_3 + 0.403W_1 + 0.064W_2 - 0.466W_3 \quad (21)$$

$S_1$, $S_2$ and $S_3$ denote the three levels of speed while $W_1$, $W_2$ and $W_3$ represent the three levels of weight considered.

**Table 5.** ANOVA for performance evaluation of the palm nut cracking machine

| **CT** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
| Speed | 2 | 4.74 | 0.43% | 4.74 | 2.372 | 0.28 | 0.77 |
| Weight | 2 | 1062.21 | 96.48% | 1062.21 | 531.104 | 62.57 | 0.001 |
| Error | 4 | 33.95 | 3.08% | 33.95 | 8.488 | | |
| Total | 8 | 1100.9 | 100.00% | | | | |
| **CN** | | | | | | | |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
| Speed | 2 | 0.0233 | 0.20% | 0.0233 | 0.01163 | 0.94 | 0.462 |
| Weight | 2 | 11.4314 | 99.37% | 11.4314 | 5.7157 | 462.97 | 0.000 |
| Error | 4 | 0.0494 | 0.43% | 0.0494 | 0.01235 | | |
| Total | 8 | 11.5041 | 100.00% | | | | |
| **PCN** | | | | | | | |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
| Speed | 2 | 0.01535 | 1.15% | 0.01535 | 0.007675 | 1 | 0.444 |
| Weight | 2 | 1.29372 | 96.57% | 1.29372 | 0.646858 | 84.46 | 0.001 |
| Error | 4 | 0.03063 | 2.29% | 0.03063 | 0.007658 | | |
| Total | 8 | 1.3397 | 100.00% | | | | |
| **UCN** | | | | | | | |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
| Speed | 2 | 0.002917 | 1.91% | 0.002917 | 0.001458 | 2.19 | 0.228 |
| Weight | 2 | 0.147217 | 96.35% | 0.147217 | 0.073608 | 110.41 | 0.000 |
| Error | 4 | 0.002667 | 1.75% | 0.002667 | 0.000667 | | |
| Total | 8 | 0.1528 | 100.00% | | | | |
| **CE** | | | | | | | |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
| Speed | 2 | 1.3472 | 39.83% | 1.3472 | 0.6736 | 4.63 | 0.091 |
| Weight | 2 | 1.4535 | 42.97% | 1.4535 | 0.7267 | 5 | 0.082 |
| Error | 4 | 0.5816 | 17.20% | 0.5816 | 0.1454 | | |
| Total | 8 | 3.3822 | 100.00% | | | | |
| **TC** | | | | | | | |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
| Speed | 2 | 0.000082 | 5.26% | 0.000082 | 0.000041 | 0.14 | 0.875 |
| Weight | 2 | 0.000287 | 18.40% | 0.000287 | 0.000144 | 0.48 | 0.649 |
| Error | 4 | 0.001193 | 76.34% | 0.001193 | 0.000298 | | |
| Total | 8 | 0.001562 | 100.00% | | | | |
| **LR** | | | | | | | |
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
| Speed | 2 | 0.2739 | 4.74% | 0.2739 | 0.137 | 0.13 | 0.885 |
| Weight | 2 | 1.1506 | 19.93% | 1.1506 | 0.5753 | 0.53 | 0.625 |
| Error | 4 | 4.3502 | 75.33% | 4.3502 | 1.0875 | | |
| Total | 8 | 5.7747 | 100.00% | | | | |

**Table 6.** Values of $R^2$ and adjusted $R^2$ for responses

| Responses | $R^2$ | Adjusted $R^2$ |
|---|---|---|
| CT | 96.92% | 93.83% |
| CN | 99.92% | 99.14% |
| PCN | 97.71% | 95.43% |
| UCN | 98.25% | 96.41% |
| CE | 82.80% | 65.61% |
| TC | 23.68% | 0.00% |
| LR | 24.67% | 0.00% |

### 3.3 Predicted optimum results

A confirmatory check was conducted in the study to precisely evaluate the correct optimization process. The attained results are used to evaluate if the values are within the confidential interval. The already attained optimal conditions for each response (output) are employed in carrying out the confirmation experiments. The outcomes of confirmation experiments, the predicted optimal value, and the CI are displayed in Table 7. The CI values reveal that the optimum values attained experimentally for each response are within a satisfactory range.

The predicted values of each of the output parameters are presented in Table 7. At the optimum condition, the CE has increased to 94.02% from the initial maximum value of 93.75%. This could also be observed that the other output parameters had also been optimized.

**Table 7.** Output values at the optimum condition

| Parameter | Optimum Conditions | Overall Mean $M_o$ | Mean at Input 1, $M_1$ | Mean at Input 2, $M_2$ | SNR Optimum Value | Predicted Optimum Value | C.I | Actual Exp. Value |
|---|---|---|---|---|---|---|---|---|
| CT | $A_1B_1$ | -28.721 | -28.488 | -23.944 | -23.711 | 15.330 | ±1.090 | 14.452 |
| CN | $A_3B_3$ | 7.586 | 7.691 | 12.093 | 12.198 | 4.073 | ±0.379 | 4.053 |
| PCN | $A_3B_1$ | 0.133 | 0.493 | 4.428 | 4.788 | 0.576 | ±0.310 | 0.671 |
| UCN | $A_1B_1$ | 12.144 | 12.798 | 17.62 | 18.274 | 0.122 | ±0.110 | 0.120 |
| CE | $A_1B_2$ | 39.386 | 39.434 | 39.416 | 39.465 | 94.022 | ±1.319 | 93.891 |
| TC | $A_1B_3$ | -17.5 | -17.25 | -16.983 | -16.733 | 0.146 | ±0.049 | 0.154 |
| LR | $A_1B_3$ | -17.499 | -17.248 | -16.983 | -16.732 | 6.864 | ±3.612 | 6.453 |

### 3.4 GRA

The grey relational grade (GRG) and ranks are estimated and displayed in Table 8. The main effects plot of the GRG and residual plots of GRG are shown in Figure 12. The highest GRG among all the experimental runs showcases the optimum multiple performance characteristics (MPC) [22, 23]. From the main effects plot of the GRG, the best conditions to achieve the optimum performance of the machine are when it is operated at 1000 rpm speed and 6 kg weight. This implies that the speed and weight to maintain optimum machine effectiveness are 1000 rpm and 6 kg, respectively. In this study, experimental run 3 gave the optimum MPC. The generated responses are displayed in Table 8 for the GRG estimation of the ranking importance of each input factor. The values of the experimental run 3 being the maximum MPC are the same as what was obtained in the main effects plot of the GRG. The orders of importance are ranked as weight > speed (Table 9).

The GRG results and percentage contribution of each parameter were evaluated using the ANOVA method. It can be observed from Table 8 that the weight of the palm nuts was the parameter that had the highest effect on the MPC with 92.22% while the speed had a 2.04% contribution. The ranking order is weight > speed with consistent results as displayed in Figure 13. The regression equation for the GRG is displayed in Eq. (22).

**Table 8.** Input parameters (speed and weight) vs. output parameter (GRG)

| Run | Speed | Weight | GRG | SNRA1 | Rank |
|---|---|---|---|---|---|
| 1 | 1000 | 2 | 0.45004 | -6.93498 | 8 |
| 2 | 1000 | 4 | 0.628695 | -4.03119 | 4 |
| 3 | 1000 | 6 | 0.796256 | -1.97894 | 1 |
| 4 | 1200 | 2 | 0.441684 | -7.09778 | 9 |
| 5 | 1200 | 4 | 0.624703 | -4.08652 | 5 |
| 6 | 1200 | 6 | 0.761667 | -2.36469 | 2 |
| 7 | 1400 | 2 | 0.494516 | -6.1164 | 7 |
| 8 | 1400 | 4 | 0.521434 | -5.65602 | 6 |
| 9 | 1400 | 6 | 0.726729 | -2.77255 | 3 |

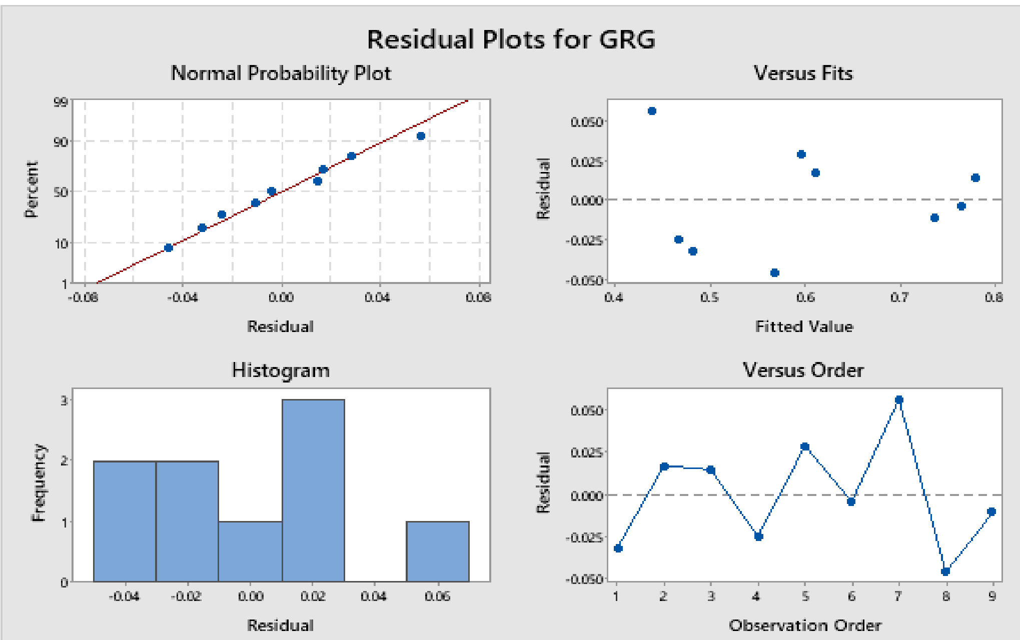



**Figure 12.** Residual plots for GRG

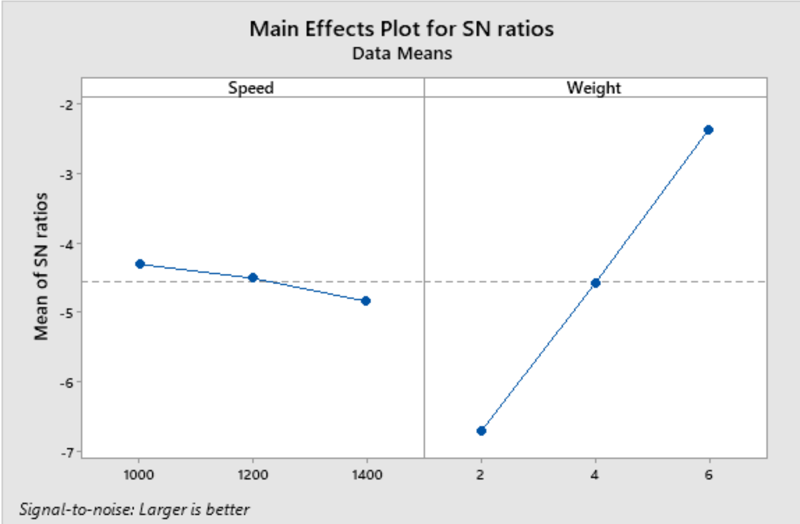



**Figure 13.** Taguchi analysis: GRG versus speed and weight

**Table 9.** Analysis of variance of GRG

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-value | p-value |
|---|---|---|---|---|---|---|---|
| Speed | 2 | 0.003000 | 2.04% | 0.003000 | 0.001500 | 0.71 | 0.544 |
| Weight | 2 | 0.135341 | 92.22% | 0.135341 | 0.067670 | 32.13 | 0.003 |
| Error | 4 | 0.008425 | 5.74% | 0.008425 | 0.002106 | | |
| Total | 8 | 0.146766 | 100.00% | | | | |

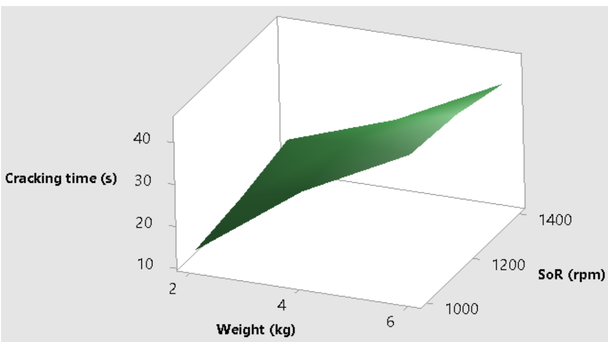
Regression Equation

$$GRG = 0.6051 + 0.0199S_1 + 0.0043S_2 - 0.0242S_3 - 0.143W_1 - 0.0135W_2 + 0.1565W_3 \quad (22)$$

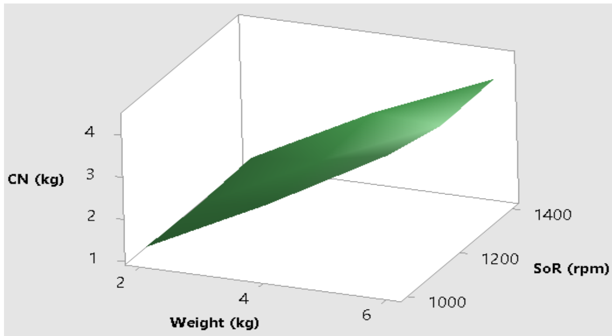
where, $S_1$ = SoR (1000 rpm), $S_2$ = SoR (1200 rpm), $S_3$ = SoR (1400 rpm), $W_1$ = Weight (2 kg), $W_2$ = Weight (4 kg), and $W_3$ = Weight (6 kg).

### 3.5 Effect of weight and speed of rotation on the responses

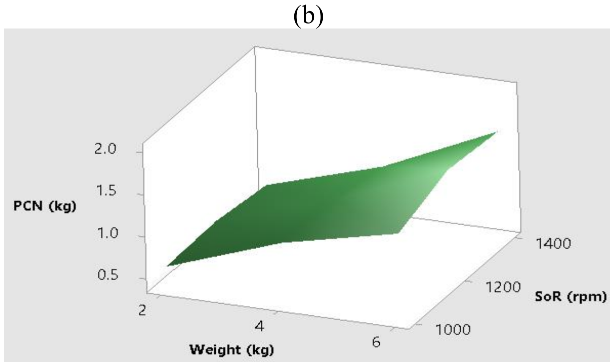
***Cracking time:*** The palm nuts' cracking time and weight showed direct variation. The cracking time depends mainly on the weight of the palm nut processed per time. Though, the contribution of the speed of rotation is very small, its effect is considered significant in cracking a hard nut like palm nut. Increase in the speed of rotation reduces the cracking time. Hence, the relation between the speed of rotation and cracking time is inverse. This observation might be attributed to the increased speed of rotation of the shaft which has caused a higher number of impacts of the cracking hammers on the palm nuts. Figure 14(a) displays the surface plot of the cracking time with respect to the speed of rotation and weight.



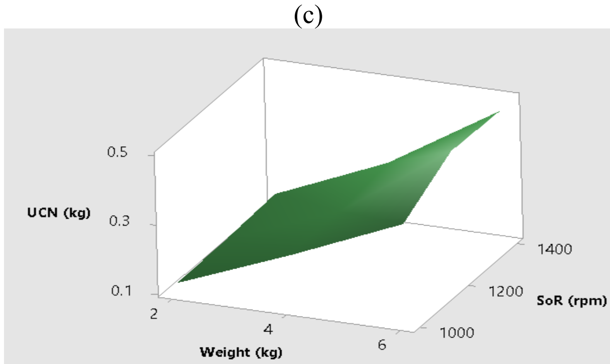

(a)



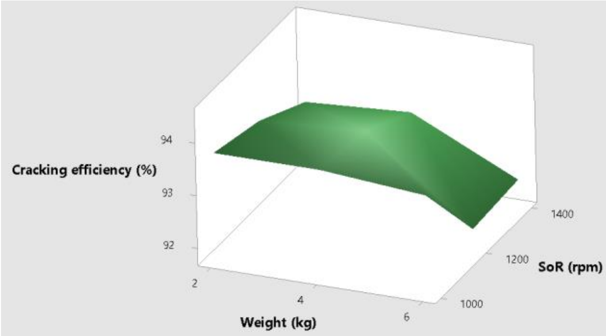

(b)



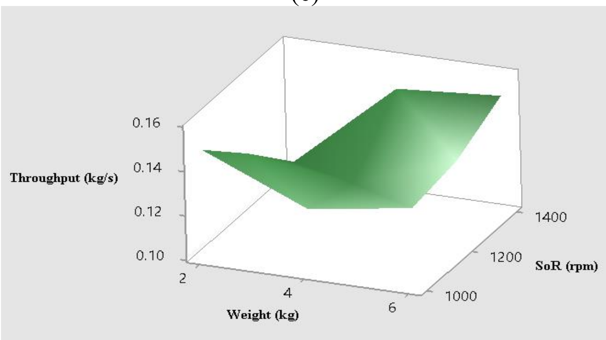

(c)



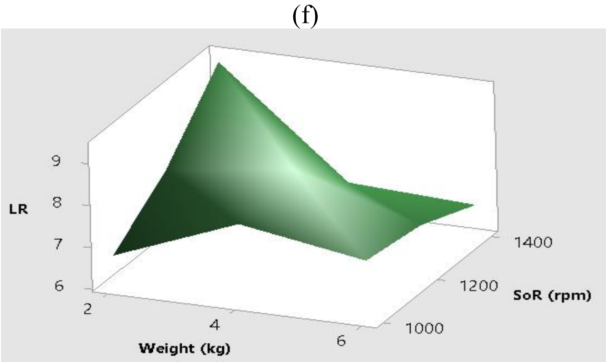

(d)




(e)




(f)




(g)

**Figure 14.** Surface plot of (a) cracking time (b) cracked nuts (c) partially cracked nuts (d) uncracked nuts (e) cracking efficiency (f) throughput capacity (g) labour requirement vs. speed of rotation and weight

***Cracked nuts, partially cracked nuts, and uncracked nuts***: Figures 14(b)-(d) display the respective surface plots of the cracked nuts, partially cracked nuts, and uncracked nuts with respect to the speed of rotation and weight. As both the speed of rotation and weight of the palm nuts increased, the values of CN, PCN, and UCN showed increment. The quantity of cracked nuts is expected to increase with speed and weight. More so, with more amount of palm nuts in the machine, the number of partially cracked nuts and uncracked nuts is expected to increase.

***Cracking efficiency***: According to Komolafe et al. [15], increased rotation speed is linked to increased machine efficiency. However, the high speed could cause more deformation on products to be cracked or dehulled. In this study, the efficiency of the machine is better at low speed of rotation (1000 rpm) while the weight of the palm nuts has no specific pattern of effects on the efficiency (Figure 14(e)). This was also noticed with the ANOVA analysis of the cracking efficiency considering the input parameters. For a cocoa depodding machine in the study of Iyanda et al. [24], an increase in speed resulted in decreased efficiency. Also, it was reported that an increase in the speed of a locust bean dehuller reduced the qualitative efficiency of the machine [21]. However, when depodding melon seeds, the efficiency increased with the speed of rotation of the machine [25] which negates the observed response in this present study.

***Throughput capacity and Labour requirement:*** Increasing the speed of rotation leads to increased TC. This is because the hammers on the shaft of the machine are allowed to work at higher speeds. This makes them have more impact on the palm nuts. Similar trends are observed in other studies [15, 21, 24]. However, TC is an inverse function of LR. This implies that at a higher speed of rotation, less time is needed for cracking operation. Hence, higher TC implies lower LR.

The efficiency and throughput of a palm nut cracking machine is generally improved through increasing the shaft speed. These parameters my reduce after reaching a certain point. Higher feed weights of the palm kernel nut, mostly at lower moisture content, results in increased cracking efficiency. The cracking time decreases with increased shaft speed while throughput increases with increased shaft speed. At optimal shaft speed, the performance of the machine and its efficiency are maximized. However, reduction inefficiency and rise in uncracked nuts may result when the speed increases beyond the optimal speed [7, 26].

For instance, Umani et al. [26] reported increased percentage of whole kernel from 34.50 to 97.80% as the cracking speed increased from 1600 to 2800 rpm. However, there was reduction of the whole kernel percentage from 95.7 to 74.3% as the cracking speed increased from 2962 to 3550 rpm. Ndukwu and Asoegwu [27] obtained whole kernel recovery ranging from 63.78 to 84.56% when the cracking speed of the vertical-shaft centrifugal palm nut cracking machine was between 1650 and 2230 rpm, when a mobile palm nut cracker was developed, 90 – 98% whole kernel recovery was obtained as the cracking speed increased between 1200 and 2400 rpm [28]. Using a horizontal-shaft centrifugal palm nut cracker at cracking speed between 1200 and 2200 rpm, the percentage whole recovery of the kernels was between 64.08 and 80.20% [29]. In the study of Ibiyeye et al. [7], where a palm kernel nut cracking unit was developed and evaluated, the cracking speeds were varied as 1000, 1200, 1350, and 1800 rpm for weights 5, 6, and 7 kg. The maximum cracking efficiency of 89% was obtained at 1000 rpm, which was the lowest speed. Whole kernel recovery percentage is significantly affected by increased speed.

During the performance evaluation of the palm kernel nut cracker developed by Okunola et al. [30], three nut sizes (14.50, 22.15, and 29.43 mm) of *Tenera* varieties and cracking speeds (970, 1200, 1450, 1750, and 2430 rpm were utilized. The cracking speed was reported to significantly affect the performance of the machine. Although, at higher speeds, the number of crushed nuts was higher, reducing the whole kernel recovery efficiency. For a maximum quality performance efficiency of the developed machine at 89.5%, the lowest speed of 970 rpm, average nut size of 29.4 mm, and moisture content of 7% were the parameters obtained.

With several studies attaining different palm kernel recovery percentage, these variations could be linked to the developed cracking mechanism, variety and size of the palm kernel nuts, as well as the moisture content of the palm kernel nuts [26].

## 4. CONCLUSION

In this study, the influences of the input parameters on the performance of the developed palm kernel cracker using the Taguchi-Grey relational analysis approach were determined. The Taguchi method showed that both the speed and weight had significant effects on the various responses. However, the effect of the weight was ranked more important with response CT, CN, PCN, UCN, TC, and LR, while speed was ranked more important for CE. The study revealed the average cracking efficiency of the machine to be around 93%, showing a high machine performance in cracking the nuts. The optimal values for each response were obtained. The GRG optimal value when the input parameters were ranked was achieved when the speed was 1000 rpm and the weight was 6 kg. the experimental values and predicted values were found to be in close proximity with minimal deviations. The mathematical models developed for the responses were considered to suitably relate to the observation.

It is recommended that further comprehensive experimental investigations and tests should be carried out under different operational conditions. Furthermore, long-term performance evaluation should be done on the developed machine. Speed modifications and part modifications of the machine could be done to enhance the efficiency of the machine. Other optimization techniques can be utilized in the performance evaluation of the developed machine.

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