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# Design, Fabrication, and Optimization of Jatropha Sheller

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**Abstract.** A study designed, fabricated, and optimized performance of a jatropha sheller, consisting of mainframe, rotary cylinder, stationary cylinder, transmission system. Evaluation and optimization considered moisture content, clearance, and roller speed as independent parameters while the responses comprised of recovery, bulk density factor, shelling capacity, energy utilization of sheller, whole kernel recovery, oil recovery, and energy utilization by extruder.
Moisture content failed to affect the response variables. The clearance affected response variables except energy utilization of the extruder. Roller speed affected shelling capacity, whole kernel recovery, and energy utilization of the extruder. Optimization resulted in operating conditions of 9.5%wb moisture content, clearance of 6 mm, and roller speed of 750 rpm.

**Keywords:** Design; Fabrication; Optimization; Jatropha; Sheller; Extrusion; Response surface.
**AMS Classification:** 62K20, 90-04, 90-08.

## 1. Introduction

*Jatropha curcas* L. is a drought resistant perennial shrub (Figure 1) averaging 3 meters in height but can grow up to 6 meters [1]. Jatropha is a smooth, erect, and widely branched shrub, whose leaves are entire, angular, or somewhat three to fivelobed, orbicular-ovate, and 100 to 180 mm long. The flowers are greenish white at 7 to 8 mm in diameter [2]. The capsules or fruits are green and fleshy. At first they contain three valves which later split when they become dry. All or two of these valves contain black oblong seed [1].

The production of soap and candle requires the use seed extract as a raw material. The leaves and bark on the other hand, become ingredients of other various industrial and pharmaceutical purposes [3]. Locally, the roots, flowers, and latex of the plant serve as herbal medicine [4]. A presser-expeller can easily extract oil from the jatropha nut [4]. About 25-30% of the jatropha, seed composed the oil, while oil is 50-60% of the kernel [5].

**Figure 1.** *Jatropha curcas* plant

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Three kilos of seeds can produce about 1 liter of oil. The NIIR Board of Consultants and Engineers [6] mentioned that jatropha seeds contain 6.62% moisture, 18.2% protein, 38% fat, 17.3% carbohydrates, 15.5% fiber, 4.5% ash and oil containing 21% unsaturated fatty acids. The Centre for Jatropha Promotion and Biodiesel [7] suggested sun during seeds for several hours or roasted for 10 minutes but not over done before extracting the oil from the seeds to break the cells containing the oil. The heat also liquefies the oil thus improving the extraction process. Oil extractions can be mechanical by using a screw press or by using a solvent such as hexane, which yields higher amount up to 99% of the total oil content. Mechanical oil extraction produces press cake constituting 6% Nitrogen, 75% Phosphorus, and 0.94% Potassium, used like chicken manure as organic fertilizer. An application of 1 ton press cake is equivalent to 200 kg of mineral fertilizer (NPK 12:24:12). In the light of the spiraling fuel increases, development of fuel energy resources to supply the needs of the Philippine industries is needed.

The development of a jatropha sheller shall contribute to the efficiency of processing the crop to fuel oil by reducing the energy required for extrusion, increasing extraction efficiency, and increasing the oil recovery. The study designed a jatropha sheller and optimized the performance at different operational parameters with optimum efficiencies and minimum energy consumption. Specifically, the study aimed at designing a sheller that efficiently removes the hulls prior to extrusion; determine the effects of seed moisture contents, drum clearance, and drum speed on the efficiencies of shelling; and determine the optimum conditions of the prototype operating conditions on recovery, bulk density factor, shelling capacity, energy utilization of sheller, whole kernel recovery, oil recovery, and energy utilization of extruder.

## 2. Materials and Methods

### 2.1. Design and fabrication of the sheller

Figure 2 shows the schematic diagram of component parts of the jatropha sheller. Figures 3 and 4 show the fabricated components and working model of the Jatropha sheller.

### 2.2. Experimental design and data analysis

The experimental design (Table 1) followed the Box and Behnken Design [8] that resulted in 15 runs. Seed moisture content (9.5, 13, and 16.5% MCwb), clearance (2, 4, and 6mm), and roller speed (300, 600, and 900 rpm) served as independent factors, while the response variables included shelling efficiency (Y1), shelling capacity (Y2), power consumption (Y3), bulk density increase factor (Y4), power consumption (Y5), shelling efficiency (Y6), and power used by extruder (Y7). Table 1 shows the experimental design of uncoded variables.

Response surface methodology (RSM) of the Statistical Analysis System (SAS) ver. 8 generated the Analysis of variance (ANOVA), contour plots, while STATISTICA ver. 7 analyzed and optimized responses within the limits of the independent factors tested. Each response follows the linear equation in the form of the following:

$$Y = \beta_0 - \beta_{k1}X_1 - \beta_{k2}X_2 + \beta_{k3}X_3 + \beta_{11}X_1^2 + \beta_{21}X_2X_1 + \beta_{22}X_2^2 + \beta_{31}X_3X_1 + \beta_{31}X_3X_2 - \beta_{33}X_3^2$$

where:

$Y$ : response variable,
$\beta_0$ : intercept,
$\beta_{k1}, \beta_{k2}, \ldots, \beta_{33}$ : coefficients,
$X_1, X_2, X_3$ : independent variables.

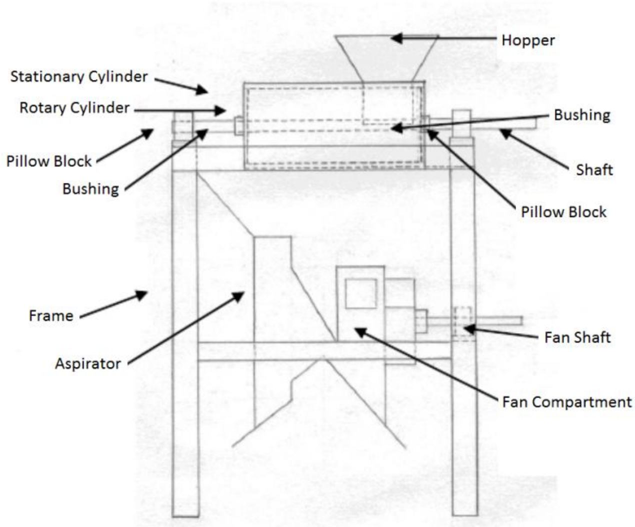


**Figure 2:** Schematic diagram of jatropha sheller

**Figure 3.**Rotating shelling cylinders

**Table 1.** Experimental design showing the un-coded variables

| Run | Moisture Content (% wet basis), $X_1$ | Clearance (mm), $X_2$ | Roller Speed (rpm), $X_3$ | Shelling Efficiency $Y_1$, % | Shelling Capacity (kg/hr) | Power Consumption, $Y_3$, W | Bulk Density Factor, $Y_4$ | Power Consumption, $Y_5$, W | Shelling Efficiency, $Y_6$, W | Power used by extruder, $Y_7$, W |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.5 | 2 | 600 | - | - | - | - | - | - | - |
| 2 | 16.5 | 2 | 600 | - | - | - | - | - | - | - |
| 3 | 9.5 | 6 | 600 | - | - | - | - | - | - | - |
| 4 | 16.5 | 6 | 600 | - | - | - | - | - | - | - |
| 5 | 13.0 | 4 | 600 | - | - | - | - | - | - | - |
| 6 | 9.5 | 4 | 300 | - | - | - | - | - | - | - |
| 7 | 16.5 | 4 | 300 | - | - | - | - | - | - | - |
| 8 | 9.5 | 4 | 900 | - | - | - | - | - | - | - |
| 9 | 16.5 | 4 | 900 | - | - | - | - | - | - | - |
| 10 | 13.0 | 4 | 600 | - | - | - | - | - | - | - |
| 11 | 13.0 | 2 | 300 | - | - | - | - | - | - | - |
| 12 | 13.0 | 6 | 300 | - | - | - | - | - | - | - |
| 13 | 13.0 | 2 | 900 | - | - | - | - | - | - | - |
| 14 | 13.0 | 6 | 900 | - | - | - | - | - | - | - |
| 15 | 13.0 | 4 | 600 | - | - | - | - | - | - | - |

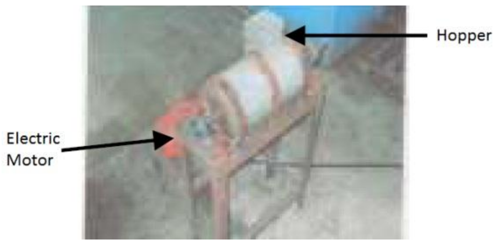


**Figure 4.** The fabricated sheller

## 2.3. Samples preparation

Fifty- (50) kilograms jatropha seeds procured from Phil Forest, Inc. served as the working samples. The samples were in storage for about nine months, dried under the sun prior to storage. Gravimetric method determined the initial moisture content of the samples. Three randomly picked 50-gram samples were prepared per run for initial moisture content determination, placed in a pre-weighed aluminum container inside Carbolite® oven at 105˚C for three days.

Equation 1 expresses the initial moisture content of the seeds as:

$$MC_{db} = \frac{Wt_i - Wt_f}{Wt_i} \times 100\% \tag{1}$$

where;

$MC_{db}$ = percent initial moisture content dry basis, (%);
$Wt_i$ = initial weight of sample, (g); and
$Wt_f$ = final weight of sample, (g).

## 2.4. Conditioning of samples

Some of the samples required conditioning to the desired level of moisture content due to inherent low moisture content of 10%wb. Runs having 13.0% and 16.5% required addition of moisture
Some of the samples required conditioning to the desired level of moisture content due to inherent low moisture content of 10%wb. Runs having 13.0% and 16.5% required addition of moisture
to meet the desired levels. The following formulas calculated the amount of water added expressed as:

$$Wtd = Wts_i \times \frac{1}{1 + MC_{dbi}} \tag{2}$$

$$Wtw_a = Wts_i - Wtd \tag{3}$$

$$Wtw_r = Wtw_a \times \frac{MC_{dbf}}{MC_{dbi}} \tag{4}$$

$$Wtw_{deficit} = Wtw_r - Wtw_a \tag{5}$$

where;

$Wtw_{deficit}$ = amount of moisture to be added, (g);
$Wt_d$ = weight of dry mass,
$Wts_i$ = initial weight of sample,
$MC_{dbf}$ = decimal moisture content dry basis,
$MC_{dbi}$ = decimal initial moisture content dry basis,
$Wtw_a$ = weight of water,
$Wtw_r$ = total weight of water required to achieve desired level.

Conditioning of samples used a manual sprayer to the desired moisture levels. Plastic jars contained the samples, securely covered and left overnight at ambient conditions for further distribution of moisture in jatropha.

## 2.5. Initial bulk density determination

A graduated cylinder (6cm x 6cm x 30cm) measured the volume of the jatropha seeds then weighed using Ohaus™ electronic balance. Equation 6 expresses the initial bulk density as:

$$\rho_{bulk\ initial} = \frac{Wt_{sample}}{Vol_{sample}} \tag{6}$$

where;

$\rho_{bulk\ initial}$ = initial bulk density,
$Wt_{sample}$ = weight of sample (kg),
$Vol_{sample}$ = volume of sample (m$^3$).

## 2.6. Machine preparation prior to shelling

The sheller operated at designated roller speed, clearance, and moisture content of the samples during each run. A clamp-on ammeter measured the current used by the motor without and with loads. A hand-held tachometer measured the rpm and aided the adjustment of the roller speed to the desired levels.

## 2.7. Performance evaluation and optimization

Sorting and classifying sheller outputs using sieves and screens (12/64, 6/64, and 4/64) followed shelling. Large particles considered samples that failed to pass the 12/64 sieve and further classified using 6/64 and 4/64 screens. Weighing each class followed classification.

### 2.7.1. Shelling recovery

The recovery describes the ability to remove shell and out of the cylinder. After each run, the sheller was disassembled to collect the remaining materials retained inside the shelling cylinder. Ohaus™ electronic balance weighed all collected materials and recorded. Equation 7 expresses the shelling recovery as:

$$Shelling\ Recovery = \frac{W_s}{Wt_{total}} \times 100\% \tag{7}$$

where;

$W_s$ = weight of shelled and discharged seeds,
$Wt_{total}$ = total weight of input seeds for shelling.

### 2.7.2. Oil recovery

A laboratory extruder expelled out the oil contained in the shelled jatropha seeds. Ohaus® electronic balance determined the weight of the shelled samples and a graduated cylinder collected of the oil extracted. Equation 8 determines the oil recovery as:

$$Oil\ Recovery = \frac{Wt_{expelled}}{Wt_{total}} \times 100\% \tag{8}$$

where;

$Oil\ Recovery$ = percentage recovered after expelling, %,
$Wt_{expelled}$ = weight of expelled oil,
$Wt_{total}$ = total weight of the sample expelled.

### 2.7.3. Final bulk density determination

Final bulk density determination followed procedures for initial bulk density.

### 2.7.4. Bulk density factor

The bulk density factor (BDF) is the ratio of the final bulk density and the initial bulk density. This describes how small particles behave resulting from shelling and addition of moistures where a BDF closes to 1.0 is an ideal condition; while greater than 1 implies that shelling operation produces more fine particles that are undesirable. Equation 9 expresses bulk density factor as:

$$BDF = \frac{\rho_{bulk\ final}}{\rho_{bulk\ initial}} \tag{9}$$

where;

$BDF$ = bulk density factor (ratio),
$\rho_{bulk\ final}$ = bulk density after shelling, (kg/m$^3$),
$\rho_{bulk\ initial}$ = bulk density before shelling, (kg/m$^3$).

### 2.7.5. Shelling efficiency

The shelling efficiency pertains to the amount of output successfully dislodged from the sheller. All experiment runs exhibited a shelling efficiency of 100%, hence excluded in the analysis. The following formula determined the shelling efficiency expressed as:

$$Shelling\ Efficiency = \frac{Wt_{shelledoutput}}{Wt_{total}} \tag{10}$$

where;

$Wt_{shelledoutput}$ = weight of product which was successfully shelled,
$Wt_{total}$ = total weight of seeds processed.

### 2.7.6. Shelling capacity

The shelling capacity pertains to the amount of material processed for a given duration of time

(1hr). Each run noted the time spent to shell 400g sample. Equation 11 expresses shelling capacity as:

$$Shelling\ Capacity = \frac{Wt_i}{t} \quad (11)$$

where;

$Shelling\ Capacity$ = amount shelled, kg/hr)

$Wt_i$ = initial weight of seeds before shelling, (kg),

$t$ = shelling time, (hr).

**Table 2.** Summary of experimental results

| Run | MC(%), | Clearance (mm), | Roller Speed (rpm), | Shelling Recovery (%) | Bulk Density Factor, (ratio) | Shelling Capacity (kg/hr) | Energy Utilization Sheller (W) | Whole Kernel Recovery (%) | Oil Recovery (%) | Energy Utilization Extruder (W) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.5 | 2 | 600 | 19.81 | 1.6 | 4.4 | 142.4 | 0.0 | 11.9 | 612.4 |
| 2 | 16.5 | 2 | 600 | 11.56 | 1.6 | 4.2 | 150.2 | 0.0 | 9.0 | 460.8 |
| 3 | 9.5 | 6 | 600 | 96.63 | 1.0 | 96.1 | 6.8 | 31.5 | 16.9 | 536.2 |
| 4 | 16.5 | 6 | 600 | 99.08 | 1.1 | 90.1 | 7.3 | 28.3 | 19.5 | 793.1 |
| 5 | 13.0 | 4 | 600 | 81.76 | 1.2 | 28.8 | 22.7 | 7.6 | 12.4 | 530.5 |
| 6 | 9.5 | 4 | 300 | 98.17 | 1.2 | 20.8 | 31.4 | 6.3 | 9.8 | 745.8 |
| 7 | 16.5 | 4 | 300 | 62.42 | 1.3 | 13.1 | 50.0 | 6.3 | 7.2 | 511.5 |
| 8 | 9.5 | 4 | 900 | 94.82 | 1.3 | 41.2 | 15.9 | 4.1 | 7.3 | 692.6 |
| 9 | 16.5 | 4 | 900 | 54.84 | 1.4 | 22.2 | 32.4 | 3.6 | 14.9 | 796.3 |
| 10 | 13.0 | 4 | 600 | 68.83 | 1.3 | 26.7 | 25.7 | 6.2 | 7.6 | 641.0 |
| 11 | 13.0 | 2 | 300 | 40.39 | 1.5 | 4.7 | 146.2 | 0.0 | 6.6 | 498.1 |
| 12 | 13.0 | 6 | 300 | 96.26 | 1.1 | 57.6 | 11.4 | 32.9 | 14.7 | 626.7 |
| 13 | 13.0 | 2 | 900 | 22.88 | 1.5 | 5.1 | 154.2 | 0.0 | 8.5 | 853.3 |
| 14 | 13.0 | 6 | 900 | 98.33 | 1.1 | 110.8 | 5.9 | 27.7 | 22.3 | 660.1 |
| 15 | 13.0 | 4 | 600 | 70.59 | 1.2 | 26.7 | 29.2 | 4.7 | 6.8 | 692.6 |

#### 2.7.7. Power consumption

Power consumption is the electric energy usage during machine operations [9]. The ammeter reading with loads for each run was the current used by the sheller. Equation 12 expresses the power consumption as:

$$Power\ Consumption = \frac{V \times I \times PF}{ME} \quad (12)$$

where;

$Power\ Consumption =$

$V$ = potential difference, (230 Volts),

$I$ = electric current w/load, (Amperes),

$PF$ = power factor, (0.8),

$ME$ = motor efficiency, (0.85).

#### 2.7.8. Whole kernel recovery

The Whole Kernel Recovery is the ratio of the whole kernels to the total output weight. Equation 13 expresses Whole Kernel Recovery (WKR):

$$WKR = \frac{Wt_{wholekernel}}{Wt_{total}} \times 100\% \quad (13)$$

where;

$WKR$ = percent whole kernel of total weight

$Wt_{wholekernel}$ = weight of whole kernels,

$Wt_{total}$ = total weight of material.

## 3. Results and Discussions

The study designed and determined the optimum conditions of the jatropha sheller in terms of independent parameters moisture content (X1), clearance (X2), and roller speed (X3) aided by Box and Behnken three-level, three incomplete factorial design of experiments [8] and Response Surface Methodology (RSM). The response variables consisted of recovery (Y1), bulk density factor (Y2), shelling capacity (Y3), energy utilization of sheller (Y4), whole kernel recovery (Y5), oil recovery (Y6), and energy utilization by extruder (Y7). Table 2 presents the summary of the experimental results.

### 3.1. Shelling recovery

Run 4 resulted in the best shelling recovery of 99%, while Run 2 indicated the lowest at 12% (Figure 5). A high recovery is necessary to avoid clogging by the retained particles inside the cylinder. The shelling cylinder required manual emptying on clogging by disassembling the sheller that was undesirable especially during long and continuous operations.

### 3.2. Bulk density factor

Bulk density varied from 1.0 to 1.6. Runs 3, 4, 12, and 14, all with 6mm clearance, represent the best runs in terms of bulk density factor of 1.0. Runs 1 and 2 indicated the worst treatment with a bulk density factor of 1.6, signifying that shelling produced fine particles that are undesirable as Figure 5 shows. Favorable bulk density factor to shelling jatropha using the sheller fall in the region of 2 – 4 mm clearance, 15 – 17% moisture contents, and 600 to 900 rpm of the cylinder.

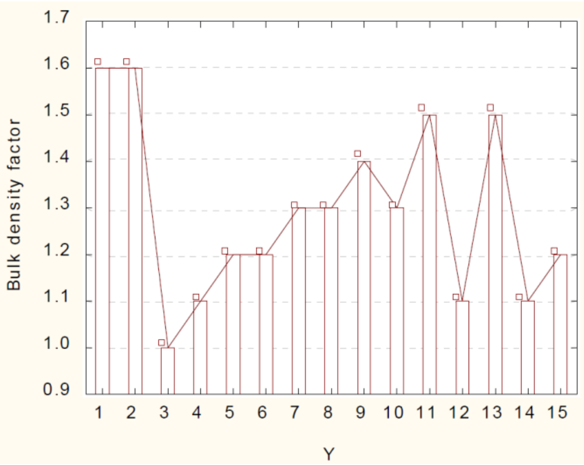


**Figure 5.** Plots of bulk density factor at different runs of the Jatropha sheller

## 3.3. Shelling capacity

Shelling capacity ranged from 4.0 to 120 kg hr-1. Run 14 exhibited the highest shelling capacity of 110.8 kg/hr, while Run 2 had the lowest with 4.2 kg/hr as indicated by Figure 6. The highest shelling capacity corresponds to the setting with the least time to process the same amount of material, or the setting that produces more materials in the same amount of time.

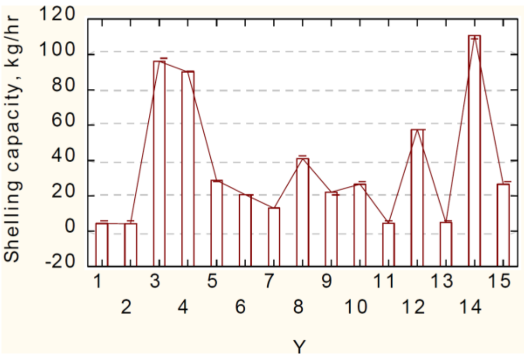


**Figure 6.**Shelling capacity at different runs of the Jatropha sheller

## 3.4. Energy utilization of sheller

Energy utilization has a direct impact on operational costs. Run 14 exhibited the lowest of 5.9W of electricity consumed while Run 13 had the highest at 154.2W (Figure 7). Energy use depends on the clearance of the shelling cylinder and housing.

## 3.5. Whole kernel recovery

Run 12 exhibited the highest whole kernel recovery of 33%. On the other hand, Runs 1, 2, 11, and 13 resulted in the worst, having 0% whole kernel recovery (Figure 8). The assessment based on a percentage of the total weight, such that 100% recovery is actually unattainable because the weight of the shell was included in the total weight.

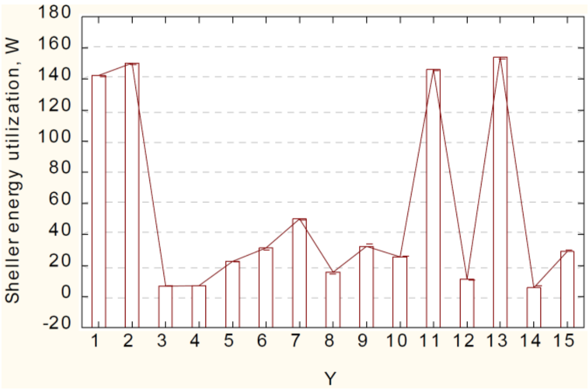


**Figure 7.** Energy utilization at different runs of the Jatropha sheller

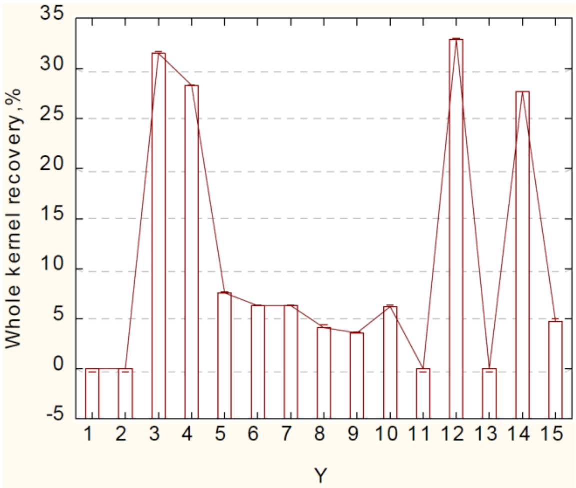


**Figure 8.** Whole kernel recovery (%) at different runs of the Jatropha sheller

### 3.6. Oil recovery

The oil recovery showed that Run 14 with pure kernels sample, obtained the highest oil recovery of 22.0% way below the potential of 38% discussed by Lele [10], and Duke [1], while Run 11 exhibited the lowest at 6.0% (Figure 9). Extrusion runs with pure kernel samples resulted in high recoveries. Expectations considered these results since more oil is actually present in 50g of pure kernel than 50g of shell and kernel mixtures.

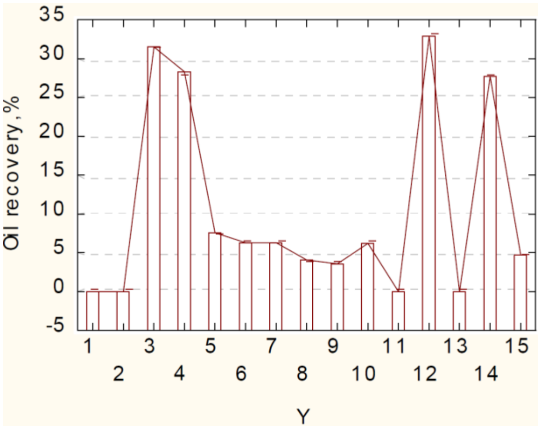


**Figure 9.** Oil recovery (%) at different runs of the Jatropha sheller

### 3.7. Energy utilization by extruder

Energy utilization of the extruder highly depends on the cleanliness of the Jatropha seeds fed as the seed coats harden during extrusion and will increase the power in expelling the oil. Hence, effective shelling of the seeds will result in lesser power. Extrusion Run 2 showed the lowest of 460.0W, considered as the best while Run 13 had the highest with 833.0W. Extrusion of jatropha after shelling indicated dependence on clearance of the shelling cylinder with 6mm as the best. In contrast, runs with the least clearance of 2mm exhibited the poor results (Table 2 and Figure 10). The minimum clearance of 2mm resulted in low recovery and the forming of press cake on the surface of the stationary cylinder. In addition, shelling using the highest speed of 900 rpm resulted in fine particles forming a loose cake in the hopper probably due to the high kinetic energy from the roller.

### 3.8. Effects of independent parameters on responses

RSReg procedure of SAS v8.0 for windows analyzed ANOVA to determine the significant effects of the independent parameters on the responses. Table 3 presents the ANOVA results

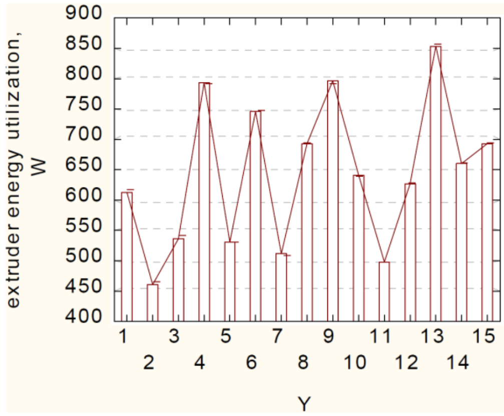


**Figure 10.** Extruder energy utilization (W) at different runs

for the significant effects of Moisture Content (X1), Clearance (X2), and Roller Speed (X3) on the response variables.

Moisture contents (X1) 9.5 to 16.5% failed to show significant effects to any of the response variables. Experimental runs showed differences in quality of the cakes during runs with clogging that resulted with treatment at different moisture levels. Treatments with lower moisture contents had rough cakes than those with higher moisture content levels. The clearance (X2) affected significantly the response variables except for the energy utilization of the extruder (Y7); shows that clearance is a critical parameter in the design of the sheller for jatropha seeds. Runs pointed that the maximum clearance resulted in shorter durations of the shelling operation, larger sizes of products, and clogging was not a problem.The roller speed (X3) affected the shelling capacity (Y3) at a 95% level of significance, whole kernel recovery (Y5) and energy utilization of the extruder (Y7) at 90% level of significance. The significant effect of the roller speed during shelling to the whole kernel recovery possibly affected the energy utilization of the extruder.

Table 4 reflects the significant effects of the regressor variables and their interactions on the responses. Clearance (X2) affected the bulk density factor (Y2), shelling capacity (Y3), energy utilization by the sheller (Y4), whole kernel recovery (Y5), and oil recovery (Y6) at a 95% level of significance. The interaction of the moisture content (X1) and clearance (X2) affected the energy utilization by the extruder at a 90% level of significance. The interaction of moisture content (X1) affected recovery (Y1) at a 90% level of significance. In addition, it also affected bulk density factor (Y2), shelling capacity (Y3), energy utilization by the sheller (Y4), whole kernel recovery (Y5), and oil recovery (Y6) at a 95% level of significance. The interaction of moisture content (X1) and roller speed (X3) affected oil recovery at a 90% level of significance. The interaction of clearance (X2) and roller speed (X3) affected shelling capacity (Y3) and whole kernel recovery (Y5) at a 95% level of significance. The rest of the parameters failed to show significant effects on the response variables.

**Table 3.** ANOVA showing the level of significance of the effects of the independent parameters on the response variables

| Variable | Degrees of Freedom | Sum of Squares Recovery ($Y_1$) | Bulk Density Factor ($Y_2$) | Capacity ($Y_3$) | Energy Utilization by Sheller ($Y_4$) | Whole Kernel Recovery ($Y_5$) | Oil Recovery ($Y_6$) | Energy Utilization by Extruder ($Y_7$) |
|---|---|---|---|---|---|---|---|---|
| Moisture Content, $X_1$ | 4 | $877.70^{ns}$ | $0.020^{ns}$ | $177.48^{ns}$ | 262.44 | $5.86^{ns}$ | $40.53^{ns}$ | $70408^{ns}$ |
| Clearance, $X_2$ | 4 | $11885.00^{**}$ | $0.396^{**}$ | $16442.00^{**}$ | $48337.00^{**}$ | $2154.27^{**}$ | $259.71^{**}$ | $74315^{ns}$ |
| Roller Speed, $X_3$ | 4 | $309.97^{ns}$ | $0.005^{ns}$ | $1638.30^{**}$ | $242.15^{ns}$ | $20.76^{*}$ | $60.95^{ns}$ | $116744^{*}$ |

$^{**}$: significant level at 95%; $^{*}$: significant level at 90%; $^{ns}$: not significant

**Table 4.** Significance of effects of independent variables on the response variables

| Run | MC(%), | Clearance (mm), | Roller Speed (rpm), | Shelling Recovery (%) | Bulk Density Factor, (ratio) | Shelling Capacity (kg/hr) | Energy Utilization Sheller (W) |
|---|---|---|---|---|---|---|---|
| X1 | ns | ns | ns | ns | ns | ns | ns |
| X2 | ns | ** | ** | ** | ** | ** | ns |
| X3 | ns | ns | ns | ns | ns | ns | ns |
| X1*X1 | ns | ns | ns | ns | ns | ns | ns |
| X2*X1 | ns | ns | ns | ns | ns | ns | * |
| X2*X2 | * | ** | ** | ** | ** | ** | ns |
| X3*X1 | ns | ns | ns | ns | ns | * | ns |
| X3*X2 | ns | ns | ** | ns | ** | ns | ns |
| X3*X3 | ns | ns | ns | ns | ns | ns | ns |

$^{**}$: significant level at 95%; $^{*}$: significant level at 90%; $^{ns}$: not significant

### 3.9. Response surface regression methodology optimization

ANOVA shows the significance of the response surface models as linear, quadratic, cross product (interaction) terms. In addition, results indicate the R2 and coefficient of variation of the results for each response (Table 5). Responses have shown linear model equations at 95% level of significance except for energy utilization by the extruder (Y7). Shelling capacity (Y3), energy utilization of the sheller (Y4), and whole kernel recovery (Y5) exhibited quadratic models at 95% level of significance, while oil recovery (Y6) at 90% level of significance. Cross product of shelling capacity (Y3) was significant at 95% level while energy utilization of the extruder was significant at 90% level of significance.

Total model for all responses had 95% level of significance except extruder energy utilization

(Y7). Shelling capacity exhibited a lack of fit at a 95% level of significance indicating high variations in data collected. All other responses exhibited no significant lack of fit.

A good model has an $R^2$ value close to 1 and a coefficient of variation close to zero. All responses resulted in $R^2$ of more than 0.9, except for energy utilization of the extruder (Y7) with 0.82. Models with an $R^2$ value near to unity describe adequately the data and predicted with much accuracy.

Table 6 presents values of the second order polynomial regression coefficients to predict responses.

**Table 5.** ANOVA showing the significance of response surface regression models

| Source of Variation | Degrees of Freedom | Sum of Squares<br>Recovery ($Y_1$) | Bulk Density Factor ($Y_2$) | Capacity ($Y_3$) | Energy Utilization by Sheller ($Y_4$) | Whole Kernel Recovery ($Y_5$) | Oil Recovery ($Y_6$) | Energy Utilization by Extruder ($Y_7$) |
|---|---|---|---|---|---|---|---|---|
| Model | 9 | $1229^{**}$ | $0.4179^{**}$ | $17572^{**}$ | $48705^{**}$ | $2180.14^{**}$ | $318.58^{**}$ | $166186^{ns}$ |
| Linear | 3 | $11845^{**}$ | $0.4026^{**}$ | $15140^{**}$ | $39796^{**}$ | $1829.20^{**}$ | $205.20^{**}$ | $52727^{ns}$ |
| Quadratic | 3 | $1017.71^{ns}$ | $0.0120^{ns}$ | $1693.70^{**}$ | $8848.98^{**}$ | $341.29^{**}$ | $71.87^{*}$ | $17268^{ns}$ |
| Cross Product | 3 | $128.94^{ns}$ | $0.0032^{ns}$ | $738.93^{**}$ | $60.15^{ns}$ | $9.65^{ns}$ | $41.52^{ns}$ | $96191^{*}$ |
| Residual | 5 | 848.4 | 0.0074 | 174.21 | 273.01 | 5.202 | 29.50 | 36598 |
| Lack of Fit | 3 | $750.11^{ns}$ | $0.0068^{ns}$ | $171.29^{**}$ | $251.90^{ns}$ | $1.025^{ns}$ | $11.00^{ns}$ | $22887^{ns}$ |
| Pure Error | 2 | 98.35 | 0.0006 | 2.93 | 21.10 | 4.17 | 18.49 | 13711 |
| $R^2$ | | 0.9387 | 0.9825 | 0.9902 | 0.9904 | 0.9976 | 0.9153 | 0.8195 |
| CV (%) | | 19.23 | 2.99 | 16.03 | 13.33 | 9.61 | 20.76 | 13.30 |

$^{**}$: significant level at 95%; $^{*}$: significant level at 90%; $^{ns}$: not significant

**Table 6.** Regression coefficients of the second-order polynomials

| Source of Variation | Recovery ($Y_1$) | Bulk Density Factor ($Y_2$) | Capacity ($Y_3$) | Energy Utilization by Sheller ($Y_4$) | Whole Kernel Recovery ($Y_5$) | Oil Recovery ($Y_6$) | Energy Utilization by Extruder ($Y_7$) |
|---|---|---|---|---|---|---|---|
| $ß_0$ | 12.186 | 1.9276 | 35.32 | 362.91 | -4.3462 | 59.84 | 1690.35 |
| $ß_1$ | 0.2594 | -0.0163 | 0.0991 | -1.1069 | 1.7311 | -4.3715 | -114.13 |
| $ß_2$ | 38.67 | -0.2615 | -31.03 | -126.15 | -8.5642 | -10.2221 | -49.53 |
| $ß_3$ | -0.1074 | 0.0002 | 0.0292 | -0.0452 | 0.0115 | -0.0322 | -1.0787 |
| $ß_{11}$ | -0.1575 | 0.0011 | 0.0443 | 0.1544 | -0.0519 | 0.089 | 0.2527 |
| $ß_{21}$ | 0.3821 | 0.0029 | -0.2068 | -0.2621 | -0.115 | 0.1939 | 14.592 |
| $ß_{22}$ | -3.7568 | 0.0141 | 5.1905 | 12.227 | 2.3643 | 1.0761 | -5.9681 |
| $ß_{31}$ | -0.001 | -0.00002 | -0.0027 | -0.0005 | -0.000093 | 0.0024 | 0.0805 |
| $ß_{32}$ | 0.0082 | 0.000004 | 0.022 | -0.0056 | -0.0022 | 0.0024 | -0.1341 |
| $ß_{33}$ | 0.000064 | 0.00000007 | -0.00004 | 0.00005 | -0.0000047 | -0.000002 | 0.00069 |

From Table 6, we can write the predictive equations for each response variable as:

$$Y_1 = 29.155 - 1.399M + 36.72C - 0.114S - 0.0703M^2 + 0.3764CM - 3.4772C^2 - 0.001SM + 0.074SC + 0.00072S^2 \quad (15)$$

$$Y_2 = 1.9276 - 0.0163M - 0.2615C + 0.002S + 0.00117M^2 + 0.00029CM + 0.0141C^2 - 0.00002SM + 0.00004SC + 0.0000007S^2 \quad (16)$$

$$Y_3 = 35.32 + 0.0991M - 31.03C + 0.02292S + 0.0443M^2 - 0.2068CM + 5.1905C^2 - 0.0027SM0.022SC - 0.00004S^2 \quad (17)$$

$$Y_4 = 362.91 - 1.1069M - 126.15C - 0.0452S + 0.1544M^2 - 0.2621CM + 12.2272C^2 0.0005SM - 0.0056SC + 0.00005S^2 \quad (18)$$

$$Y_5 = -4.3462 + 1.7311M - 8.5642C + 0.0115S - 0.0519M^2 \mp 0.1939CM + 1.0761C^2 - 0.000093SM - 0.0022SC - 0.000047S^2 \quad (19)$$

$$Y_6 = 59.84 - 4.3715M - 10.2221C - 0.0322S + 0.089M^2 + 14.5925CM - 5.9681C^2 + 0.0024SM + 0.0024SC - 0.0000023S^2 \quad (20)$$

$$Y_7 = 1690.35 - 114.13M - 49.53C - 1.0787S + 0.2527M^2 + 14.5925CM - 5.9681C^2 + 0.0805SM - 0.1341SC + 0.0069S^2 \quad (21)$$

where;

$M =$ moisture content (9.5 to 16.5%) $_{db}$,
$C =$ clearance (2 to 6mm),
$S =$ shaft speed (300 to 900 rpm).

### 3.9.1. Localizing the optimum conditions for the jatropha sheller

The main objective in determining the optimum condition of the shelling process is to obtain the highest recovery, shelling capacity, whole kernel recovery, and oil recovery, and to obtain the lowest bulk density factor and energy utilization for the shelling and extrusion. Statistica 7.0 determined the profiles of the predicted values and the desirability for each of the response variables by response surface regression of general linear model at optimum shelling conditions (Table 7 and Figure 11) by conducting 100 iterations are to arrive at optimum shelling conditions of the sheller.

Iterations and Regression analysis resulted in optimum conditions of 9.5% moisture content level, 6mm clearance, and a 750-rpm roller speed with 89% desirability. This shows that running the experiment at the optimum conditions will produce the same predicted responses at 89% probability, which is high for pioneer research activities.

### 3.9.2. Verification of the optimum conditions

Three (3) verification runs validated the most likely optimum condition of 9.5% moisture content, a clearance of 6mm, and a roller speed of 750 rpm. Verification entails comparing the mean values obtained from the verification runs to the predicted values of the generated models as Table 8 presents.

Predicted and actual shelling recovery of 104 was higher than 98.1% during verification run. Bulk density factor did not differ with 1.04 and 1.06, for predicted and verification runs, respectively; similarly found in shelling capacity and whole kernel recovery. The predicted sheller energy utilization (0.54 W) was way below the verification run of 6.9W but within the values obtained when running at 16.5% moisture content (Table 7). This means that the actual sheller energy use from three (3) verification runs was quite near to mean values and variations can be in seeds compositions. However, considering a variation of 6.36 is still an acceptable value for agricultural research results (CV = .20 or 20% max) considerations as explained by Gomez and Gomez [11].

The predicted and observed energy (306W) for extruder varied probably due to the current fluctuations during verification runs.

Nevertheless, verification runs confirmed well the predicted values at optimum conditions with acceptable percentage variations from predicted values except for energy utilizations for sheller and extruder.

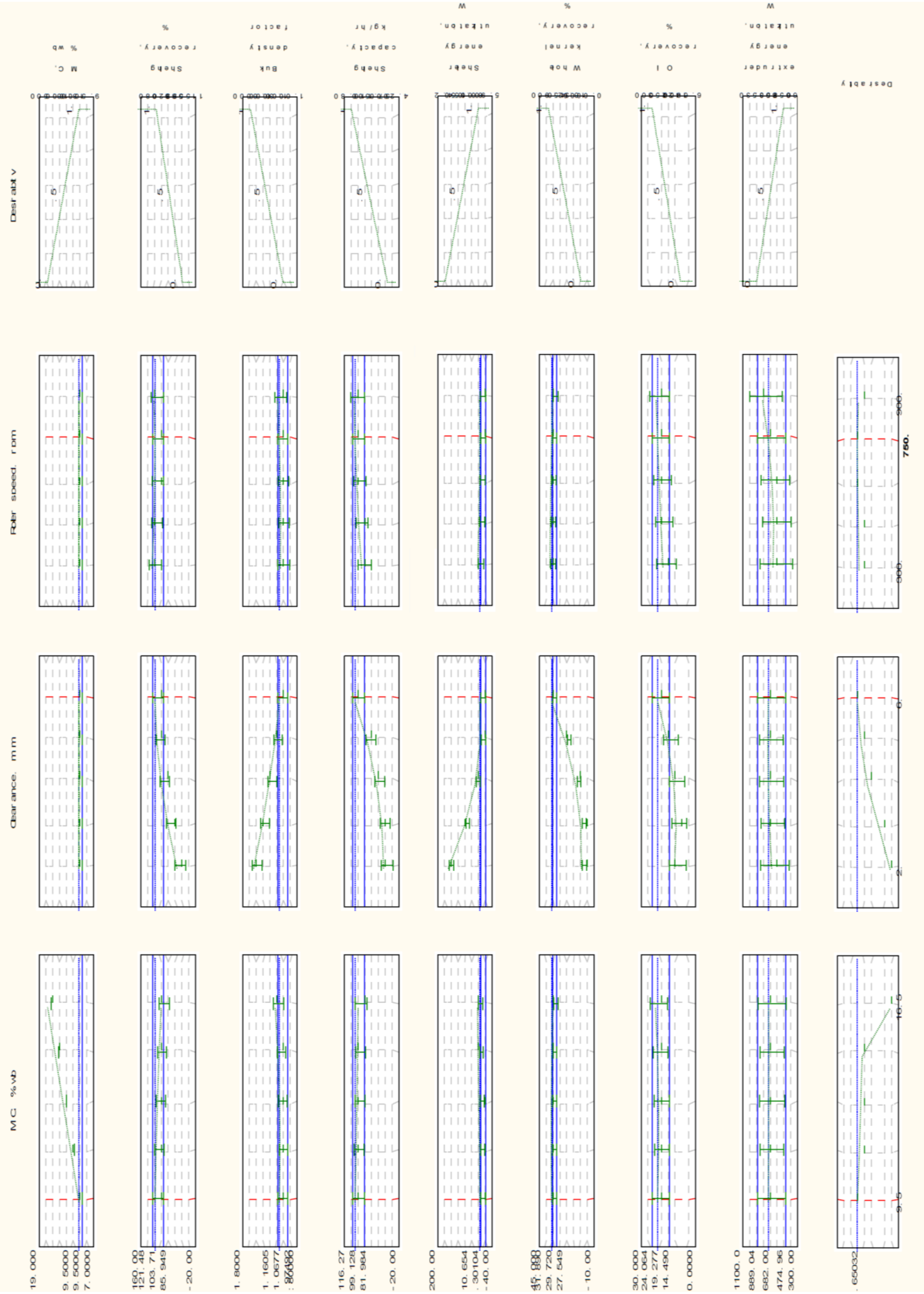

**Figure11.** Profiles of predicted values and desirability of the Jatropha sheller

**Table 7.** Predicted responses at optimum shelling conditions*

| Factor | Factor Level | Predicted Shelling Recovery | Predicted Bulk Density Factor | Predicted Capacity | Predicted Sheller Energy | Predicted Whole Kernel Recovery | Predicted Oil Recovery | Predicted Extruder Energy | Desirability Value |
|---|---|---|---|---|---|---|---|---|---|
| **MC** | **9.50** | **104.35** | **1.04** | **108.83** | **0.54** | **29.88** | **17.54** | **493.75** | **0.89** |
| MC | 11.25 | 102.40 | 1.065 | 105.05 | 0.55 | 29.70 | 18.20 | 566.24 | 0.86 |
| MC | 13.00 | 99.49 | 1.08 | 101.55 | 1.52 | 29.19 | 19.40 | 640.30 | 0.83 |
| MC | 14.75 | 95.60 | 1.11 | 98.32 | 3.43 | 28.35 | 21.14 | 715.91 | 0.79 |
| MC | 16.50 | 90.74 | 1.14 | 95.36 | 6.30 | 27.18 | 23.42 | 793.09 | 0.72 |
| CLEARANCE | 2.00 | 33.54 | 1.47 | 10.18 | 141.03 | -0.58 | 9.01 | 755.99 | 0.28 |
| CLEARANCE | 3.00 | 60.74 | 1.35 | 18.76 | 69.91 | 0.02 | 8.04 | 702.38 | 0.41 |
| CLEARANCE | 4.00 | 81.60 | 1.23 | 38.06 | 22.79 | 5.30 | 9.14 | 640.80 | 0.55 |
| CLEARANCE | 5.00 | 96.14 | 1.13 | 68.09 | -0.3317 | 15.25 | 12.31 | 571.26 | 0.71 |
| **CLEARANCE** | **6.00** | **104.35** | **1.04** | **108.33** | **0.54** | **29.88** | **17.54** | **493.75** | **0.89** |
| SPEED | 300.00 | 103.25 | 0.97 | 64.61 | 12.61 | 33.36 | 16.19 | 656.15 | 0.78 |
| SPEED | 450.00 | 101.92 | 0.99 | 81.50 | 5.81 | 32.37 | 16.66 | 574.96 | 0.84 |
| SPEED | 600.00 | 102.28 | 1.01 | 96.24 | 1.79 | 31.21 | 17.11 | 520.83 | 0.87 |
| **SPEED** | **750.00** | **104.35** | **1.04** | **108.33** | **0.54** | **29.88** | **17.54** | **493.75** | **0.89** |
| SPEED | 900.00 | 108.12 | 1.07 | 119.28 | 2.08 | 28.38 | 17.95 | 493.74 | 0.89 |

* Optimum conditions for shelling are highlighted as shown above

Table 8 shows that the least accurate predictive model equation was the one for sheller energy utilization (Y4) which has 92% deviation from the actual verification values with Y5 and Y6 have the most accurate predictive model equation with only 4.0% deviation.

**Table 8.** Comparison between predicted results and verification run results

| Response Variables | Predicted Values from Statistica | Mean Values from Verification Run | Standard Deviation from Verification Run | % Deviation |
|---|---|---|---|---|
| $Y_1$, Recovery (%) | **104.3** | **98.1** | **6.2** | **6.0** |
| $Y_2$, Bulk Density Factor (ratio) | 1.04 | 1.06 | 0.02 | 2.0 |
| $Y_3$, Capacity (kg/hr) | 108.8 | 101.2 | 7.6 | 7.0 |
| $Y_4$, Energy Utilization by Sheller (kJ) | 0.54 | 6.9 | 6.36 | 92.0 |
| $Y_5$, Whole Kernel Recovery (%) | 29.9 | 31.0 | 1.1 | 4.0 |
| $Y_6$, Oil Recovery (%) | 17.5 | 18.3 | 0.8 | 4.0 |
| $Y_7$, Energy Utilization by Extruder (kJ) | 493.8 | 799.7 | 305.9 | 62.0 |

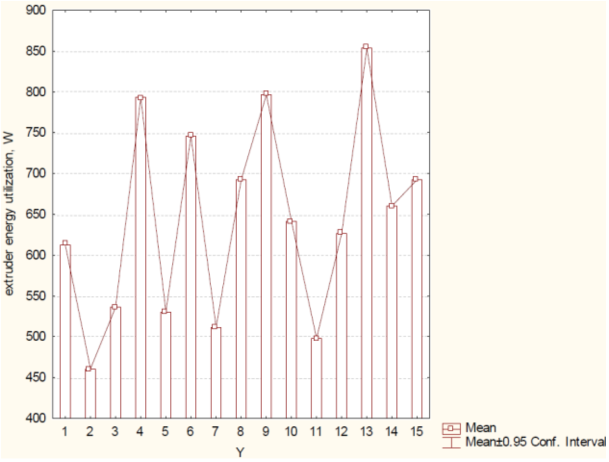


**Figure 12.** Extruder energy utilization (W) at different runs

### 3.10. Effects of independent parameters on responses

RSReg procedure of SAS v8.0 for windows analyzed ANOVA to determine the significant effects of the independent parameters on the responses. Table 3 presents the ANOVA results for the significant effects of Moisture Content (X1), Clearance (X2), and Roller Speed (X3) on the response variables.

Moisture contents (X1) 9.5 to 16.5% failed to show significant effects to any of the response variables. Experimental runs showed differences in quality of the cakes during runs with clogging that resulted with treatment at different moisture levels. Treatments with lower moisture contents had rough cakes than those with higher moisture content levels.

The clearance (X2) affected significantly the response variables except for the energy utilization of the extruder (Y7) which shows that clearance is a critical parameter in the design of the sheller for jatropha seeds. Runs pointed that the maximum clearance resulted in shorter durations of the shelling operation, larger sizes of products, and clogging was not a problem.

The roller speed (X3) affected the shelling capacity (Y3) at a 95% level of significance, whole kernel recovery (Y5) and energy utilization of the extruder (Y7) at 90% level of significance. The significant effect of the roller speed during shelling to the whole kernel recovery possibly affected the energy utilization of the extruder.

## 4. Summary and Conclusion

A jatropha sheller has been designed, tested and optimized in terms of moisture content (X1), clearance (X2), and roller speed (X3) based on the experimental results of the responses consisting of recovery (Y1), bulk density factor (Y2), shelling capacity (Y3), energy utilization of sheller (Y4), whole kernel recovery (Y5), oil recovery (Y6), and energy utilization by extruder (Y7).

## 5. Recommendations

To improve further research on the efficiency of the sheller, future study or studies must consider:
*Belt Slippage* – A chain and sprocket transmission shall improve power transmission;
*Low whole kernels recovery* – Increasing the clearance between the punches of the stationary and rotary cylinder to the next higher increments (8mm, 10mm, and 12mm) offers ideas for further study;
*Clogging resulting in low recovery* – The spiral orientation of the rows of punches in the sheller failed to convey small particles to the end of the stationary cylinder. Modifying the discharged mechanism of shelled material from the stationary cylinder is recommended;
*Relatively low capacity* –Providing a hopper that is as much as the length of the cylinder is recommended.

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