# OPTIMIZATION OF MILLING PROCESS OF HAMMER MILL USING RESPONSE SURFACE METHODOLOGY (RSM)

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***Abstract***
*Milling operation is one of the most used size reduction techniques in several household and food processing industries. Optimization of the milling process of a hammer mill that consists of a shaft fitted with 18 swinging hammers and a screen situated below the chamber was carried out using response surface methodology (RSM) with three factors (Moisture content, machine speed, and feed rate) and three responses (Milling efficiency, milling capacity, and particle mean diameter) for two varieties of maize (DMRSTWM and DMRSTYM). Maize sample of known weight was introduced through the hopper to the hammer mill operated at constant machine speed and responses were determined using gravimetric methods. The result shows that the optimum machine performance values for DMRSTWM variety were 92.98%, 94.77 g/s, and 0.28 mm for the milling efficiency, milling capacity and particle mean diameter respectively with 0.966 desirability value while the obtained optimum machine performance values for DMRSTYM variety were 94.85%, 100.96g/s, and 0.29 mm for the milling efficiency, milling capacity and particle mean diameter of the milled product respectively with 0.950 desirability value. To obtain amaximized milling efficiency and milling capacity with a finely milled product the milling machine should be operated at the machine speed of 2964.21 rpm, a feed rate of 180 kg/h and 4.00% moisture content for DMRSTWM varieties and machine speed of 2795.76 rpm, a feed rate of 177.99 kg/h and 4.00% moisture content for DMRSTYM varieties, this findings could be applied in both small and large scale feed and food processing industries.*

Keywords: Hammer mill, Maize, Modelling, Optimization, Response surface methodology

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## 1. INTRODUCTION

Milling mechanism was mostly used in several household and industrial food processors, some of its application requires large and heavy machines with relatively high energy consumption while others are in the smaller unit which consumes lesser power. A hammer mill is the most applied machine for the reduction of the material of large pieces into fine segments of various grades (Toneva *at al.*, 2011a,b). Hammer mill is found in different sizes and configurations depending on their variety of applications and comes in different sizes and styles meant for a variety of applications (Patel *at al.*, 2008). However, the working mechanisms are similar.

Hammers are used for the grinding process in each of the different types used in various industries. It is quite important to know the various components of a hammer mill to understand how it works. It has a steel drum that contains hammers mounted on a central shaft. The shaft is connected to a mortar through a series of gears or belt drives. The gears are used to vary its speed depending on the preference of the user. As the shaft rotates, it swings the hammers and makes them crush large pieces fed into the machine. As the hammers grind on the large pieces, they push finely ground pieces to screen filters. The pieces are allowed to pass through selectively depending on their sizes (Toneva *at al.*, 2011a,b).The performance of hammer mills are greatly affected by several factors such as hammer speed, hammer configuration, hammer position, the nature of the material, structure of the material, condition of the material (Naik and Chaudhuri, 2015; Dey *at al.*, 2013; Mani *at al.*, 2004: Yu *at al.*, 2003)

According to Gilmour (2006), response surface methodology (RSM) was created by box and collaborators in the 50's and consists of a collection of mathematical and statistical techniques that are focused on the application of empirical models to the experimental values in relation to experimental design. The Linear or square polynomial functions are used to describe the system studied and, subsequently, to test experimental conditions (modeling and displacement) until the desired objective is attained and the scenario is optimized (Teofilo and Fereira, 2006).

There are several hammer mill that is in existence but many have major limitation such as the inability to produce uniform grinding at high revolution per minute (rpm) (Xuan *at al.*, 2012) Also, their cost of operation is too high as their power requirements may be too high if it is not optimally utilized. Considering the micronization of huge agricultural products it is essential to optimize, model, and improve the hammer mill performance to maximize its operation efficiency. To this end, this study aims at the optimization of milling process ofhammer mill with swinging hammers using response surface methodology (RSM).

## 2. MATERIALS AND METHODS

### 2.1 Sample Collection and Preparation

Two varieties of maize (DMRSTYM and DMRSTWM) grains wereobtained from a grain store in Oja Oba market, Akure south local government, Ondo state, Nigeria, the grains were cleaned, sorted and gradedto remove dirt, foreign material,broken grains and damaged grains from the whole grain. The moisture content of the grains was determined using the standard oven drying method (gravimetric method) and the moisture content was calculated using equation 1

$$Mc = \frac{M_w - M_d}{M_w} \times 100 \qquad (1)$$

Where the Mc is the moisture content of the grain on a wet basis, $M_w$ is the wet mass of the grain, and $M_d$is the dry mass of the grain.

However, the variation in the moisture content was done either by drying of the maize sample in the laboratory of at 50 $^oC$ or by addition of distilled water,the amount of water to be added or removed from sample was calculated from the relationship reported by Ozumba and Obiakor (2011) as shown in equation 2.

$$Q = \left(\frac{100 - MC_i}{100 - MC_d} - 1\right) \times W_s \qquad (2)$$

Where Q is the quantity of water (g) to be added or removed to the sample, $MC_i$ is the initial moisture content of the grain, $MC_d$ is the desired moisture content and $W_s$ is the weight of the samples (g)

### 2.2 Machine and Operational Descriptions

The hammer mill used in this study was designed and fabricated in the Department Agricultural and Environmental Engineering Workshop. It consists of a shaft assembly on which 18 swinging hammers are mounted and a screen (perforated sheet metal) was situated below the hammers. When the material is fed into the grinding chamber through the hopper, it is initially struck by the rotating hammers and then thrown against the screen. Therefore, the material is crushed or shattered by the repeated hammer impacts, collisions with the grid plates and walls of the grinding chamber as well as particle on particle impacts (Kosee at al., 2001 and Shin at al., 2003). Theoretically, as soon as the particle size of the material is reduced to the size smaller than that of the holes of the screen, it will pass through the screen and separate through the outlet of the mill (Toneva at al., 2011a,b, and Xuan at al., 2012).

### 2.3 Methods

#### 2.3.1 Milling Experiment

The sample of a known weight with a specified moisture content was introduced to the milling machine through the hopper at a predetermined feed rate (regulated with feed opening). The output of the milled product from the milling machine and the time taken to complete the operation was recorded for further calculation. Digital voltmeter and ammeter were used to monitor the voltage and current respectively as the milling process proceeds to ensure when to stop the operation for each experimental run. About 200g of the milled product was characterized using mechanical sieve shaker and a rotap sieve set with different screen hole ranging from 0.125 mm to 4 mm

### 2.3.2 Determination of milling efficiency

The milling efficiency of the hammer mill was calculated based on the percentage ratio of the mass of the milled product obtained to the input mass of the grain as shown in equation 3 for all the experimental runs as reported by Kawuyo at al. (2017)

$$\eta_m = \frac{M_p}{M_i} \times 100 \qquad (3)$$

Where, $\eta_m$ is the milling efficiency, $M_p$ is the mass of the milled product and $M_i$ is the input mass of the grain

### 2.3.3 Determination of milling capacity

The milling capacity of the hammer mill was calculated using the ratio of the input mass of grain to the total time taken to milled the grain as expressed in equation 4 for all the experimental runs as reported by Kawuyo at al. (2017)

$$C = \frac{M_i}{t_m} \times 100 \qquad (4)$$

Where $C$ is the milling capacity (g/s), $M_i$ is the input mass of the grain (g)and $t_m$ is the time taken to mill product (s)

### 2.3.3 Determination of particle mean diameter

The particles mean diameter was determined using the gravimetric approach, based ASABE standard (ASABE, 2008) and the relationship is shown in equation 5 as reported by (Patwa, 2014)

$$d_{gw} = log^{-1}\frac{\sum_{i-1}^{n}(W_i d_i')}{\sum_{i-1}^{n}(W_i)} \qquad (5)$$

where $d_{gw}$ is the mean diameter of particles by mass (mm), $W_i$ is the mass on the $i^{th}$ sieve (g), n is the number of sieves, $d_i$ is the nominal sieve aperture size of the $i^{th}$ sieve (mm)

### 2.4 Statistical Analysis

Three explanatory variables which include: the grain moisture content, the feed rate, and the machine speed were considered for the performance evaluation of the hammer mill. the machine performance was determined for each level of the machine speed ranging from 1200 rpm – 3000 rpm, moisture content ranging from 4 – 16%. Wet basis and feed rate ranging from 60 – 180kg/h. A comprehensive data was recorded based on the number of experimental runs given by the number of independent parameters and its level via the full factorial rotatable design using response surface methodology (RSM) approach on design expert version 10 software as reported by Fadele at al. (2018) and the accuracy of the optimum models were expressed based on the coefficient of determination.

## 3. RESULTS AND DISCUSSION

### 3.1 Optimal Range and Goal

The numerical optimization of the milling process was carried out by super-positioning of the different responses of the milling efficiency, milling capacity andparticle mean diameter for each variety. The optimum solution was obtained by minimizing the particle mean diameter while the milling efficiency and milling capacity were maximized, the experimentally obtained result was taking as the range of optimality. For the resulted range of optimality of *DMRSTWM* variety, the milling efficiency ranges from 70.18 - 93.37%, the milling capacity ranges from 16.95 - 199.62 g/sand the particle mean diameter ranges from 0.27 - 0.59 mm, meanwhile the range of optimality of *DMRSTYM* variety shows that the milling efficiency ranges from 60.76-94.85%, the milling capacity ranges from 18.5.59-106.93 g/s and the particle mean diameter ranges from 0.27 - 0.52 mm as presented in Table 1.

### 3.2 Optimal Model

The optimum model shows that the crop and the machine parameter considered in this study depict a quadratic relationship with the milling efficiency, milling capacity of the machine, and particle mean diameter milled product of the *DMRSTWM* variety as shown in Table 2.

**Table 1: Optimality range and goal for the optimization of the machine performance**

| Variables | *DMRSTWM* | | *DMRSTYM* | | Goal |
|---|---|---|---|---|---|
| | Lower limit | Upper limit | Lower limit | Upper limit | |
| A: Machine speed (rpm) | 1200.00 | 3000.00 | 1200.00 | 3000.00 | is in range |
| B: Feed rate (kg/h) | 60.00 | 180.00 | 60.00 | 180.00 | is in range |
| C: Moisture content (%. Wet basis | 4.00 | 16.00 | 4.00 | 16.00 | is in range |
| Milling efficiency (%) | 70.180 | 93.387 | 60.763 | 94.849 | maximize |
| Milling capacity (g/s) | 16.955 | 100.621 | 18.589 | 106.931 | maximize |
| Mean particle diameter (mm) | 0.268 | 0.593 | 0.271 | 0.519 | minimize |

**Table 2: Optimal model coefficient for the milling process of *DMRSTWM* variety**

| Response | Milling efficiency (%) | Milling capacity (g/s) | Mean particle diameter (mm) |
|---|---|---|---|
| Intercept | 82.222 | 41.124 | 0.306 |
| A: Machine speed | 3.129 *** | 12.592 *** | -0.086 *** |
| B: Feed rate | 3.823 *** | 19.962 *** | 0.003 $^{Ns}$ |
| C: Moisture content | -4.457 *** | -1.555 $^{Ns}$ | 0.024 *** |
| AB | -0.609 * | 4.071 *** | -0.008 $^{Ns}$ |
| AC | -0.369 $^{Ns}$ | -0.712 $^{Ns}$ | -0.028 *** |
| BC | -1.121 *** | -4.355 *** | 0.009 $^{Ns}$ |
| $A^2$ | -0.941 * | 2.73 $^{Ns}$ | 0.064 *** |
| $B^2$ | -1.441 *** | 2.654 $^{Ns}$ | 0.001 $^{Ns}$ |
| $C^2$ | 0.887 * | 5.916 *** | 0.007 $^{Ns}$ |
| Coefficient of determination | 0.9452 *** | 0.9356 *** | 0.7696 *** |

| Keys: | | |
|---|---|---|
| | *Ns* = | Not significant ($P > 0.1$) |
| | * = | Likely significant ($0.05 < P \leq 0.1$) |
| | ** = | Significant ($0.01 < P \leq 0.5$) |
| | *** = | Highly Significant ($P \leq 0.01$) |

**Table 3: Optimal model coefficient for the milling process of *DMRSTYM* variety**

| Response | Milling efficiency (%) | Milling capacity (g/s) | Mean particle diameter (mm) |
|---|---|---|---|
| Intercept | 80.503 | 51.530 | 0.323 |
| A: Machine speed | 7.912 *** | 15.727 *** | -0.069 *** |
| B: Feed rate | 2.537 *** | 22.856 *** | 0.002 $^{Ns}$ |
| C: Moisture content | -5.443 *** | -5.149 *** | 0.029 *** |
| AB | 2.685 *** | 7.805 *** | -0.004 Ns |
| AC | 2.58 *** | -2.869 * | -0.025 *** |
| BC | -0.169 $^{Ns}$ | -1.013 Ns | -0.024 ** |
| $A^2$ | | | 0.047 *** |
| $B^2$ | | | -0.006 Ns |
| $C^2$ | | | -0.013 Ns |
| Coefficient of determination | 0.8934 *** | 0.9459 *** | 0.7696 *** |

| Keys: | | |
|---|---|---|
| | *Ns* = | Not significant (0. $P > 0.1$) |
| | * = | Likely significant ($0.05 < P \leq 0.1$) |
| | ** = | Significant ($0.01 < P \leq 0.5$) |
| | *** = | Highly Significant ($P \leq 0.01$) |

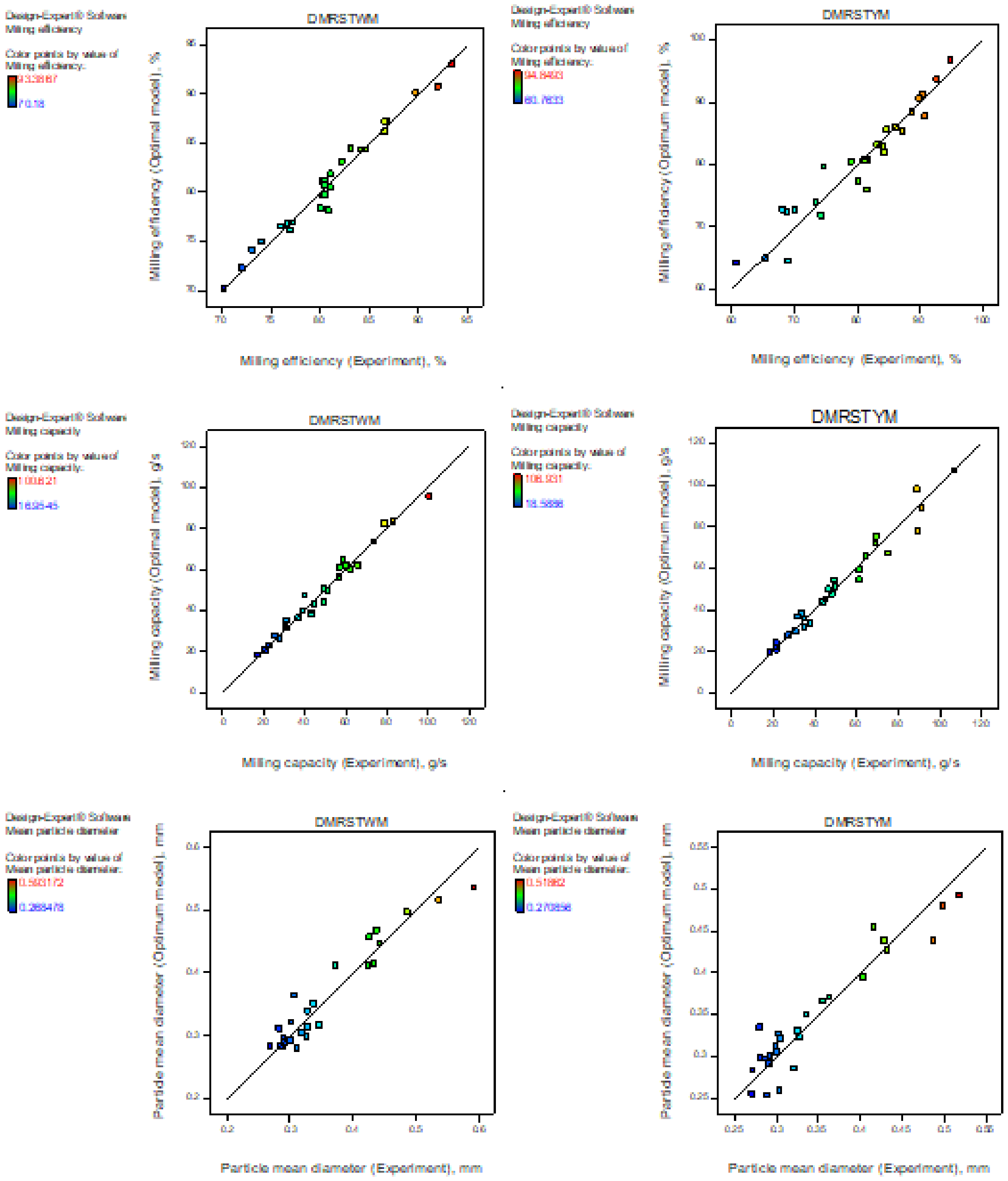

**Figure 1: Optimum model value vs experimental value**

As inferred from Table 3 for the *DMRSTYM* variety, the crop and the machine parameters show a factorial relationship with the milling efficiency and milling capacity, meanwhile, it exhibits a quadratic with the particle mean diameter of the milled product.The optimum models show a highly significant ($P < 0.01$) degree of reliability of 94.52%, 93.56%, and 76.96% in prediction of the milling efficiency, milling capacity of the machine, and particle mean diameter of the milled product respectively for *DMRSTWM* variety (Table 2) and 89.34%, 94.95%, and 76.96%, in the prediction of the milling efficiency, milling capacity of the machine, and particle mean diameter of the milled product respectively for

*DMRSTYM* variety (Table 3). The linearity between the optimum model data and the experimental values were presented in Figure 1.

## 3.3 Optimal Machine Performance

The optimum crop and machine parameter for the milling process were obtained as 4% grain moisture content, 180 kg/h feed rate and machine speed of 2964.21 rpm for *DMRSTWM* variety as shown in Table 4 and 4% grain moisture content, 177.99 kg/h feed rate and machine speed of 2795.76 rpm for *DMRSTYM* variety as shown in Table 5. The obtained optimum machine performance values for *DMRSTWM* variety are 92.98%, 94.77 g/s, and 0.28 mm for the milling efficiency, milling capacity and particle mean diameter of the milled product respectively with high desirability value of 0.966 (Table 5).The obtained optimum machine performance values for *DMRSTYM* variety are 94.85%, 100.96g/s, and 0.29 mm, for the milling efficiency, milling capacity, and particle mean diameter of the milled product respectively with high desirability value 0.950(Table 5). the optimal milling performance obtained in this study is in a close range to the result obtained by Atere *at al.* (2016) during the optimization of the milling efficiency of hammer mill for maize processing using response surface methodology (RSM) but there was a clear difference in the optimum operational parameters in which the optimum performance was obtained, the variation in this result might be due to the difference in the configuration of the hammer and the number of machine performance parameter considered in the studies, Atere *at al.* (2016) considered a single objective function approach and multi-objective functions approach was considered in this study whereas, this study agrees with the findings of Mugabi *et al.* (2019) who also consider multi-objective functions approach.

**Table 4:Optimal solutions for the milling process of *DMRSTWM*variety**

| S/N | Machine speed (rpm) | Feed rate (kg/h) | Moisture content (%) | Milling efficiency (%) | Milling capacity (g/s) | Mean particle diameter (mm) | Desirability | Remark |
|---|---|---|---|---|---|---|---|---|
| 1 | 2964.21 | 180.00 | 4.00 | 92.975 | 94.766 | 0.280 | 0.966 | Selected |
| 2 | 2971.12 | 180.00 | 4.02 | 92.953 | 94.866 | 0.280 | 0.965 | |
| 3 | 2999.99 | 180.00 | 4.16 | 92.808 | 95.173 | 0.282 | 0.963 | |
| 4 | 2999.96 | 177.24 | 4.00 | 92.947 | 94.127 | 0.283 | 0.962 | |
| 5 | 2971.34 | 175.98 | 4.00 | 92.879 | 92.709 | 0.281 | 0.959 | |
| 6 | 2975.93 | 179.75 | 4.31 | 92.587 | 93.985 | 0.280 | 0.958 | |
| 7 | 2997.26 | 174.14 | 4.00 | 92.858 | 92.335 | 0.283 | 0.956 | |
| 8 | 2975.70 | 172.83 | 4.00 | 92.793 | 91.077 | 0.282 | 0.953 | |
| 9 | 2999.99 | 170.53 | 4.00 | 92.752 | 90.418 | 0.284 | 0.950 | |
| 10 | 3000.00 | 169.41 | 4.00 | 92.714 | 89.801 | 0.285 | 0.947 | |
| 11 | 2686.93 | 179.52 | 4.00 | 92.539 | 87.798 | 0.268 | 0.935 | |
| 12 | 2733.01 | 166.70 | 4.00 | 92.202 | 82.064 | 0.272 | 0.917 | |
| 13 | 2989.82 | 152.17 | 4.00 | 92.018 | 80.373 | 0.288 | 0.913 | |
| 14 | 2866.46 | 134.67 | 4.00 | 90.858 | 68.855 | 0.284 | 0.861 | |
| 15 | 3000.00 | 180.00 | 9.29 | 86.896 | 83.994 | 0.279 | 0.838 | |
| 16 | 2999.98 | 102.27 | 4.00 | 88.716 | 56.469 | 0.300 | 0.787 | |
| 17 | 3000.00 | 180.00 | 12.12 | 84.197 | 81.533 | 0.281 | 0.777 | |
| 18 | 2999.99 | 91.68 | 4.00 | 87.756 | 51.822 | 0.303 | 0.755 | |
| 19 | 3000.00 | 166.12 | 13.75 | 82.819 | 75.291 | 0.284 | 0.733 | |
| 20 | 3000.00 | 141.96 | 13.96 | 82.326 | 65.625 | 0.284 | 0.700 | |

**Table 5:Optimal solutions for the milling process of *DMRSTYM*variety**

| S/N | Machine speed (rpm) | Feed rate (kg/h) | Moisture content (%) | Milling efficiency (%) | Milling capacity (g/s) | Particle mean diameter (mm) | Desirability | Remark |
|---|---|---|---|---|---|---|---|---|
| 1 | 2795.760 | 177.990 | 4.000 | 94.849 | 100.956 | 0.291 | 0.950 | Selected |
| 2 | 2798.990 | 179.999 | 4.048 | 94.849 | 100.984 | 0.291 | 0.950 | |
| 3 | 2804.417 | 180.000 | 4.129 | 94.849 | 101.030 | 0.291 | 0.949 | |
| 4 | 2811.784 | 179.998 | 4.240 | 94.849 | 101.089 | 0.292 | 0.949 | |
| 5 | 2815.695 | 180.000 | 4.300 | 94.849 | 101.120 | 0.292 | 0.949 | |
| 6 | 2820.164 | 179.999 | 4.368 | 94.849 | 101.154 | 0.292 | 0.949 | |
| 7 | 2826.660 | 180.000 | 4.468 | 94.849 | 101.202 | 0.293 | 0.948 | |
| 8 | 2829.805 | 179.956 | 4.511 | 94.849 | 101.211 | 0.293 | 0.948 | |
| 9 | 2811.194 | 178.290 | 4.000 | 94.849 | 100.553 | 0.291 | 0.948 | |
| 10 | 2834.140 | 179.993 | 4.584 | 94.849 | 101.252 | 0.293 | 0.948 | |
| 11 | 2830.654 | 179.493 | 4.460 | 94.849 | 101.075 | 0.293 | 0.948 | |
| 12 | 2840.727 | 179.999 | 4.689 | 94.849 | 101.297 | 0.293 | 0.948 | |
| 13 | 2839.023 | 179.798 | 4.634 | 94.849 | 101.225 | 0.293 | 0.948 | |
| 14 | 2821.097 | 177.210 | 4.000 | 94.849 | 100.300 | 0.291 | 0.947 | |
| 15 | 2861.497 | 179.998 | 5.025 | 94.849 | 101.418 | 0.294 | 0.947 | |
| 16 | 2864.765 | 179.999 | 5.079 | 94.849 | 101.434 | 0.295 | 0.947 | |
| 17 | 2868.126 | 179.999 | 5.135 | 94.849 | 101.451 | 0.295 | 0.946 | |
| 18 | 2872.965 | 179.998 | 5.215 | 94.849 | 101.474 | 0.295 | 0.946 | |
| 19 | 2774.229 | 179.955 | 4.000 | 94.654 | 100.303 | 0.290 | 0.946 | |
| 20 | 2877.276 | 180.000 | 5.288 | 94.849 | 101.494 | 0.295 | 0.946 | |

## 4. CONCLUSIONS

The following conclusions were drawn from the successful optimization of the milling process of two varieties of maize in the hammer mill using response surface methodology

i. The independent factors considered in this study depict a quadratic relationship with the milling efficiency, milling capacity of the machine, and particle mean diameter milled product of the *DMRSTWM* meanwhile, the factors depicts a factorial relationship with the milling efficiency and milling capacity, and show a quadratic relationship with the particle mean diameter of the milled product of the *DMRSTYW* at a high significance level (P<0.001).

ii. The obtained optimum machine performance values for *DMRSTWM* variety are 92.98%, and 94.77 g/s for the milling efficiency and milling capacity with optimum milled product characteristics values of 0.28 mmfor particle mean diameter of the milled product while,the obtained optimum machine performance values for *DMRSTYM* variety are 94.85%and 100.96g/s for the milling efficiencyand milling capacity respectively with optimum milled product characteristics values of 0.29 mmparticle mean diameter of the milled product.

iii. To obtain maximized milling efficiencyand milling capacity with a finely milled product the milling machine should be operated at a machine speed of 2964.21 rpm, a feed rate of 180 kg/h and 4% moisture content for *DMRSTWM* variety and machine speed of 2795.76 rpm, a feed rate of 177.99 kg/h and 4.00% moisture content for *DMRSTYM* variety.This operating condition could be applied in feed and food processing industries on both a small and large scale.

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