



## Performance Evaluation and Optimization of Split-unit Maize Dehusking and Threshing Machine

Ishola Tajudeen Abiodun<sup>a\*</sup> , Adeyi Abdulrasaq Mashood<sup>a</sup>, Akande Fatai Bukola<sup>b</sup> and Saleh Aminu<sup>c</sup> 

<sup>a</sup>Department of Agricultural and Biosystems Engineering, University of Ilorin, Kwara State, Nigeria

<sup>b</sup>Department of Agricultural Engineering, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria

<sup>c</sup>Department of Agricultural & Bio-Resources Engineering, Ahmadu Bello University, Zaria, Nigeria

\* Corresponding author. E-mail: istab@unilorin.edu.ng

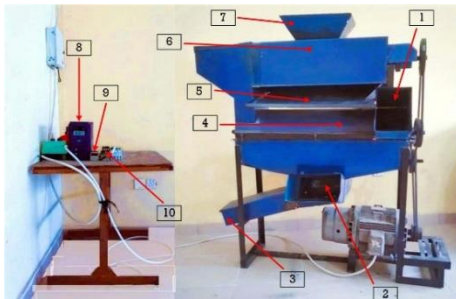
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### ABSTRACT

Manual maize dehusking is laborious, time consuming and non-economical. The dehusking unit of the existing maize dehusker cum thresher are not separated. This is responsible for large quantity of impurities in the threshed grains thereby leading to low input capacity per kilowatt hour. A split-unit maize dehusking and threshing machine was developed in an attempt to address this challenge without evaluating its performance. Hence, the focus of this research was to study the effects of moisture content (MC) and machine speed (MS) on the performance of maize dehusking and threshing machine using response surface methodology. The response variables were dehusking efficiency (DE), threshing efficiency (TE), cleaning efficiency (CE), throughput capacity (TC), mechanical damage index (MDI), total grain loss (TGL) and input capacity per kilowatt-hour (ICK). A randomized 3x3 factorial i-optimal experimental design was employed. Mathematical models relating the input variables to the performance indices were developed. The predicted optimum values obtained were validated using the values obtained from the experiment. The machine speed was discovered to have the greater effect on the response variables than moisture content for the experiments carried out. The optimization process revealed that the optimal values for the performance indices of the maize machine were obtained at the moisture content (17.09 % wet basis) and machine speed (1500 rpm). The optimum values for DE, TE, CE, TC, MDI, TGL and ICK were 98.51 %, 99.80 %, 98.9%, 315.80 kg/h, 0.51 %, 9.1 % and 651.38 kg/kWh respectively. The difference between the predicted values and the experimental values was insignificant with minor deviation for all response variables investigated. The mathematical models developed for the DE, TE, CE, TC, MDI, TGL and ICK adequately represent the relationship among variables of the study.

**Keywords:** Maize; Machine; Performance Indices; Optimization.

### Graphical abstract



Maize dehusking and threshing machine

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## 1. Introduction

Maize (*Zea Mays* L.) is an annual crop largely cultivated almost everywhere in the world and became the most recognized and planted cereal crop after rice and wheat. It is considered as one of the major cereal crops due to its numerous purposes such as food for human consumption, feed for animals and raw materials for the industries [1-4]. Maize dehusking is the removal of the husk from maize cob before threshing. In Nigeria, maize dehusking is manually done by using hands. This is tedious, labour intensive, time consuming, expensive and injurious to farmers. Threshing is the removal of grains from maize cob either manually or mechanically. The manual method involves the use of hand or stick to remove grains from the maize cob. Many research works had been done in Nigeria on the development of maize threshers of different capacities but most of them cannot handle dehusking and threshing effectively because they are basically designed to thresh maize that had already been dehusked [5-8].

An automated maize dehusking machine was designed and a 3D prototype was manufactured. The strength of the prototype was tested but a real-life machine was not produced [9]. The performance evaluation a solar powered maize dehusker cum sheller was carried out. The throughput capacity obtained was only 36.14 kg/h due to the limited capacity of the solar power source [10]. The input capacity per kilowatt-hour was not evaluated. Another maize dehusker cum sheller was developed and tested. The input capacity per kilowatt-hour obtained was 527 kg/kWh [11].

For most of the existing maize dehusker cum thresher, the dehusking unit is not separated from the threshing unit. This is responsible for large quantity of impurities in the threshed grains which need to be removed. This requirement leads to low input capacity per kilowatt hour for these machines as more power is consumed in cleaning the grains [10-12]. Hence, to overcome these challenges, there is need to develop a maize processing machine that will have a dehusking unit separated from the threshing unit and both units will be able to turn out clean grains in operation. Based on this, a split-unit maize dehusking and threshing machine was designed and constructed. However, the performance evaluation of the machine was not carried out. Therefore, the focus of this research was the performance evaluation and optimization of this split-unit maize dehusking and threshing machine using response surface methodology.

## 2. Materials and Methods

### 2.1 Sample Preparation

The maize used for testing the maize dehusking and threshing machine was planted and harvested at the Teaching and Research farm of University of Ilorin (latitude 8° 30' 00" N, longitude 4° 32' 60" E), Kwara State, Nigeria. Sorting was carried out to ensure only fully developed and dry undehusked maize cobs were used. The initial moisture content of undehusked maize was determined by using OHRUS MB 90 (1mg/0.01 %) moisture analyzer. The initial moisture content was found to be  $12 \pm 0.04$  % (wet basis). The whole sample was divided into three parts. The first part was at  $12 \pm 0.04$  % (wet basis) while the second and third parts were conditioned into  $15 \pm 0.03$  % and  $18 \pm 0.05$  % (wet basis) respectively. Each part was subdivided into three to get three replicates.

### 2.2 Experimental Design

A randomized 3x3 factorial i-optimal experimental design was employed for the performance evaluation. The levels of the machine speed were 1300, 1400 and 1500 rpm. Based on the stable moisture content after harvest, the moisture content levels were 12, 15 and 18 % (wet basis). With 3 replicates, a total of twenty-seven experiments were conducted as shown in Table 1.

### 2.3 Experimental Procedure

10 kg of dry undehusked maize was fed into the machine through the hopper for each experimental run. The machine components (Fig. 1) include hopper, dehusking chamber, threshing chamber, grain outlet, chaff outlet, husk outlet and instrumentation. The instrumentation for the machine (Fig. 2) was used to control the speed and time of operation of the machine. This comprised of Frequency inverter (Model Mdaoud 380V, 3phase, 5 hp), Electromagnetic contactor (Model Chint NXV-25, 40 Amps) and Omron digital Timer (Model DH48S-2S, 0.01s – 99h). While the Frequency inverter was used to change the speed of the electric motor as desired, the Omron digital Timer was used to accurately time the period of

operation via the control terminals of the Electromagnetic contactor.

Table 1. Outputs of the machine at selected Experimental plan

Run	MC (%)	MS (rpm)	DE (%)	TE (%)	CE (%)	TC (kg/h)	MDI (%)	TGL (%)	ICK (kg/kWh)
1	12	1300	98.00	99.10	98.00	315.79	0.35	13.60	606.84
2	12	1300	98.02	99.08	98.03	315.78	0.36	13.62	606.82
3	12	1300	98.00	99.09	98.01	315.82	0.37	13.60	606.85
4	18	1300	98.60	99.10	98.00	321.43	0.30	9.08	631.10
5	18	1300	98.58	99.10	98.01	321.44	0.30	9.07	631.11
6	18	1300	98.61	99.12	97.99	321.44	0.32	9.10	631.12
7	12	1500	97.50	99.70	99.00	310.34	0.50	14.40	633.44
8	12	1500	97.51	99.69	98.99	310.34	0.51	14.41	633.43
9	12	1500	97.53	99.68	98.98	310.35	0.51	14.42	633.45
10	18	1500	98.50	99.80	99.00	315.79	0.50	8.77	651.92
11	18	1500	98.51	99.82	98.99	315.81	0.52	8.79	651.93
12	18	1500	98.52	99.81	98.99	315.80	0.51	8.78	651.94
13	12	1400	97.72	99.51	98.50	313.03	0.46	13.90	632.69
14	12	1400	97.70	99.52	98.53	313.05	0.45	13.92	632.70
15	12	1400	97.71	99.50	98.51	313.04	0.45	13.91	632.69
16	18	1400	98.50	99.60	98.00	318.58	0.45	9.32	643.91
17	18	1400	98.51	99.61	98.02	318.57	0.47	9.32	643.90
18	18	1400	98.53	99.60	98.03	318.58	0.46	9.33	643.89
19	15	1300	98.40	99.20	98.00	318.58	0.35	9.53	601.02
20	15	1300	98.42	99.21	98.00	318.57	0.35	9.54	601.02
21	15	1300	98.41	99.22	97.99	318.59	0.37	9.55	601.03
22	15	1500	98.10	99.70	99.00	313.04	0.55	10.45	626.56
23	15	1500	98.13	99.69	98.99	313.05	0.57	10.47	626.58
24	15	1500	98.11	99.68	98.99	313.05	0.57	10.46	626.58
25	15	1400	98.20	99.50	98.50	315.79	0.51	9.38	613.71
26	15	1400	98.23	99.52	98.53	315.80	0.52	9.39	613.69
27	15	1400	98.21	99.51	98.52	315.79	0.50	9.38	613.70

MC, moisture content(wb); MS, machine speed; DE, dehusking efficiency; TE, threshing efficiency; CE, cleaning efficiency; TC, throughput capacity; MDI, mechanical damage index; TGL, total grain loss; ICK, input capacity per kWh

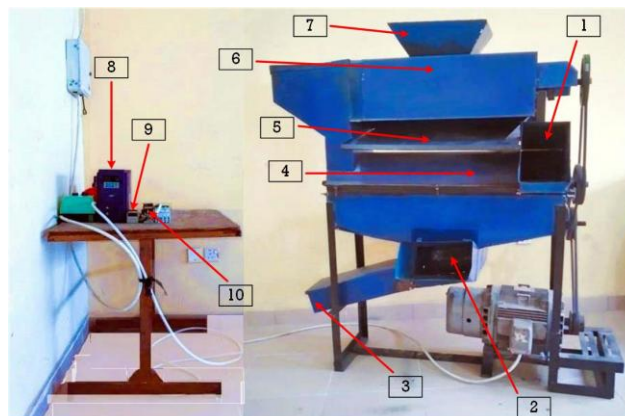


Fig 1. Maize dehusking and threshing machine.

1. Empty cobs outlet 2. Chaff outlet 3. Grains outlet 4. Threshing chamber 5. Husks outlet 6. Dehusking chamber 7. Hopper 8. Frequency inverter 9. Omron digital timer 10. Electromagnetic contactor.

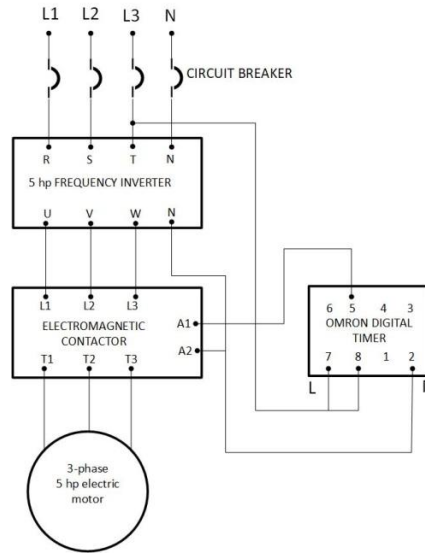


Fig 2. Schematic diagram of the instrumentation of the machine.

#### 2.4 Performance evaluation

The Nigeria Industrial Standard Code for grain threshers prepared by NSAE [13] was employed for the determination of performance indices of the maize dehusking and threshing machine.

$$\text{Dehusking efficiency}(\%) = \left(1 - \frac{G}{A}\right) \times 100 \quad (1)$$

$$\text{Threshing efficiency} (\%) = \left(1 - \frac{D}{A}\right) \times 100 \quad (2)$$

$$\text{Cleaning efficiency} (\%) = \frac{M}{F} \times 100 \quad (3)$$

$$\text{Throughput capacity} \left(\frac{kg}{h}\right) = \frac{A}{T} \quad (4)$$

$$\text{Mechanical damage index} (\%) = \frac{C}{A} \times 100 \quad (5)$$

$$\text{Total grain loss} (\%) = \frac{L}{A} \times 100 \quad (6)$$

$$\text{Input capacity per kilowatt - hour} \left(\frac{kg}{kWh}\right) = \frac{A}{T \times W} \quad (7)$$

Where T = time of test run in hours (h); A = weight of maize fed into the machine per unit time (kg); G = weight of undehusked maize collected from husk outlet per unit time (kg); C = weight of damaged grains from all outlet per unit time (kg); M = weight of cleaned grains taken from grain outlet per unit time (kg); F = total weight of grain sample taken from all outlet per unit time (kg); D = weight of damaged grain collected from all outlet per unit time (kg); L = weight of grain loss (threshed, unthreshed and undehusked) collected from all outlet (kg); W = power consumption of the prime mover (kW)

#### 2.5 Optimization of the performance of the machine

The experimental design, analysis and generation model equations which illustrate the diverse performance of the machine were conducted using the Response Surface Methodology (RSM) tool (Design-Expert version 13.0.5.0). As recommended by Fakayode et al [14], the experimental results were compared with the predicted results. The performance evaluation of the machine was carried out such that the input variables were the machine speed and moisture content of the undehusked maize and the response variables were dehusking efficiency (%), threshing efficiency (%), cleaning efficiency (%), throughput capacity (kg/h), mechanical damage index (%), percentage grain loss (%), and input capacity per kilowatt-

hour (kg/kWh). The range of moisture content (12 –18% wet basis) and machine speed (1300 –1500 rpm) was utilized in the experiment. Using linear, two-factor interaction (2FI), quadratic, and cubic models, the responses of the machine were assessed to determine which model performed best as recommended by Fakayode et al [14,15]. In order to ascertain the suitability of the generated models, analysis of variance was performed using the different responses. Also, their significance, fitness and their interactions with the performance responses was determined as done by Fadele et al [3]. Likewise, the p-value was analyzed. Optimization of the response variables was conducted. The desired responses (dehusking efficiency, threshing efficiency, cleaning efficiency, throughput capacity and input capacity per kilowatt-hour) were maximized while the undesirable responses (mechanical damage index and total grain loss) were minimized.

### 3. Results and Discussion

#### 3.1 Effects of speed and moisture content on the machine Performance indices

The machine speed and moisture content of unhusked maize were varied with respect to the selected responses (dehusking efficiency, threshing efficiency, cleaning efficiency, throughput capacity, total grain loss, mechanical damage index and input capacity per kilowatt hour to study their effects.

##### 3.1.1 Dehusking efficiency

Figure 3 is a response surface plot which depict effects of machine speed and moisture content on dehusking efficiency. It could be seen that increase in moisture content increased the dehusking efficiency. Also, as the machine speed increased, there was a slight increase in dehusking efficiency. This behavior may be attributed to the changes in properties of the unhusked maize at different moisture levels and its corresponding ease of tearing the husk as its moisture content increases. This is in line with result obtained by Dange et al [12]. Thus, the moisture content of the unhusked maize has more influence on dehusking efficiency compared to machine speed as it makes dehusking operation of the machine easier and faster.

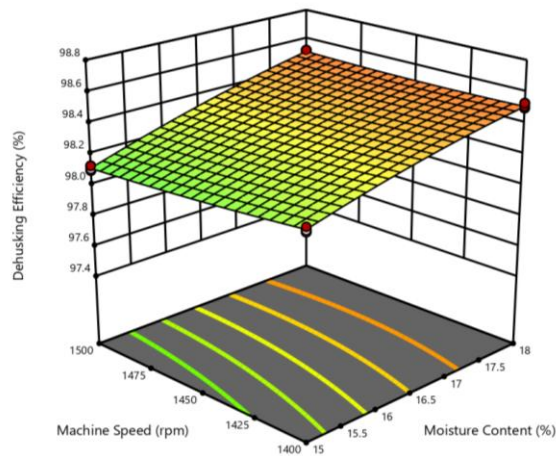


Fig 3. Effects of machine speed and moisture content on dehusking efficiency

##### 3.1.2 Threshing Efficiency

The response surface plot which shows the effects of machine speed and moisture content on threshing efficiency is shown in Fig 4. Increase in both machine speed and moisture content led to increase in the threshing efficiency of the machine. This is because increase in cylinder speed increases the number of impacts which help to get the grains detached from maize cobs easily. This is in agreement with the result obtained by [16]. However, machine speed shows more influence on threshing efficiency compared to moisture content.

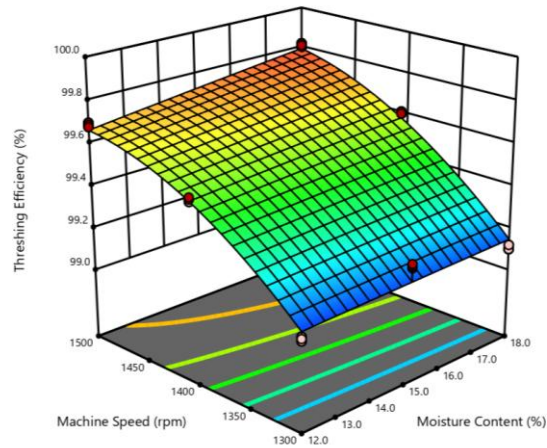


Fig 4. Effects of machine speed and moisture content on threshing efficiency

### 3.1.3 Cleaning Efficiency

Figure 5 displays the response surface plot which depicts the effect of machine speed and moisture content on cleaning efficiency. It could be seen that increase in machine speed increased cleaning efficiency while increase in moisture content led to decreased cleaning efficiency. This is in agreement with the results obtained by [17] for performance evaluation of motorized and treadle cowpea threshers. It was claimed that better cleaning efficiency at higher peripheral speeds is an obvious trend, because higher peripheral speed produces fine chaff particles which can be easily blown away by the blower. Hence, the machine speed has more influence on cleaning efficiency of the machine.

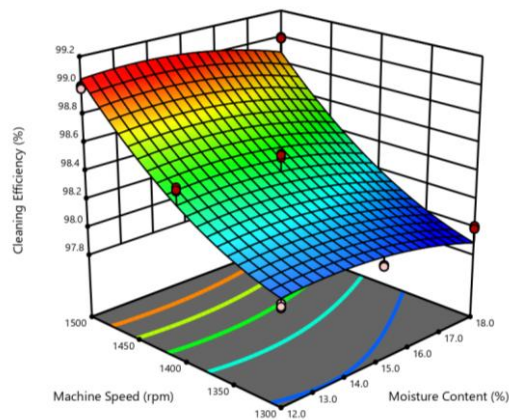


Fig 5. Effects of machine speed and moisture content on cleaning efficiency

### 3.1.4 Throughput Capacity

The effects of the interactions of machine speed and moisture content on throughput capacity of the machine is shown in Fig. 6. It was observed that as the moisture content increased, the throughput capacity increased. Contrarily, as the machine speed increased, throughput capacity decreased. This showed that moisture content of undehusked maize has more influence on throughput capacity of the machine. This is in line with the findings of [18] who claimed that maize cob spent more time in the dehusking unit at higher speed of the machine before it could move to threshing unit and thereby leading to reduction in throughput capacity of the machine. Likewise, [19] claimed that increase in speed of dehulling locust beans resulted in increased throughput capacity.

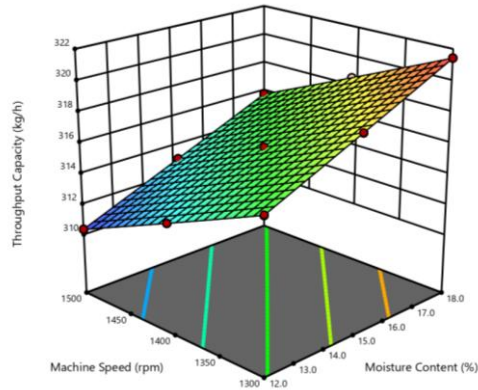


Fig 6. Effects of machine speed and moisture content on throughput capacity

### 3.1.5 Mechanical Damage Index

Figure 7 is the response surface plot showing the effects of machine speed and moisture content on mechanical damage index. It was observed that increase in machine speed increased the mechanical damage index while increase in moisture content led to decrease in mechanical damage index. This is in agreement with the results obtained by Sahu et al [16] from development of a hand operated small-scale maize sheller. Thus, the machine speed shows more influence on mechanical damage index than the moisture content of the maize husk.

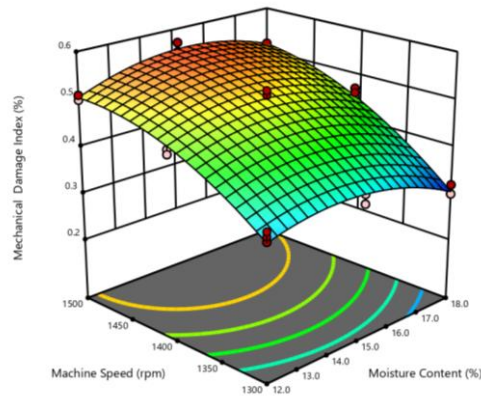


Fig 7. Effects of machine speed and moisture content on mechanical damage index

### 3.1.6 Total Grain Loss

The effects of the interactions of machine speed and moisture content on total grain loss is depicted in Fig. 8. As moisture content increased, the total grain loss decreased whereas as machine speed increased, the total grain loss slightly increased. This is because low moisture content of maize husk could aid the grain loss. Thus, the moisture content of the undehusked maize has more influence on the total grain loss of the machine compared to machine speed.

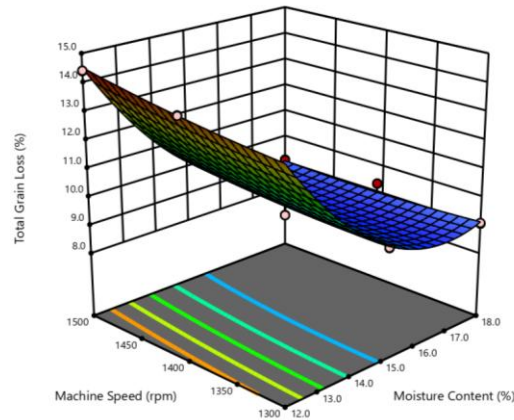


Fig 8. Effects of machine speed and moisture content on total grain loss

### 3.1.7 Input capacity per kilowatt hour

The response surface plot which shows the effects of speed of machine speed and moisture content on input capacity per kilowatt-hour is shown in Fig. 9. It could be seen that as the moisture content increased, the input capacity per kilowatt-hour decreased but later increased. Likewise, as the machine speed increased, the input capacity per kilowatt-hour increased. This implies that increase in machine speed at low moisture content prolonged the retention period of maize cob in the dehusking unit and thereby leading to reduction in the input capacity per kilowatt hour. However, when the machine speed is high and moisture content is also high, the detachment of husk will be easier from maize cob with little retention period and thereby leading to increase input capacity per kilowatt hour. However, the machine speed shows more influence on input capacity per kilowatt hour compared to moisture content of the machine.

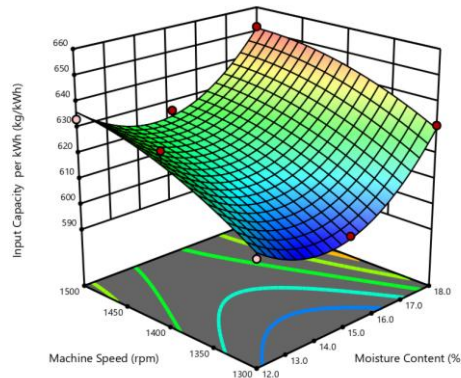


Fig 9. Effects of machine speed and moisture content on input capacity per kilowatt-hour

### 3.2 Modelling of the performance indices of the machine

Quadratic models were generated for the prediction of the performance indices of the machine. The following response equations were obtained

$$DE = 111.826 + 0.005MC - 0.019MS + 3.39 \times 10^{-4}(MC)(MS) - 0.012(MC)^2 + 4.611 \times 10^{-6}(MS)^2 \quad (8)$$

$$TE = 75.723 - 0.102MC + 0.032MS + 8.6 \times 10^{-5}(MC)(MS) - 1.85 \times 10^{-4}(MC)^2 + 1.1 \times 10^{-5}(MS)^2 \quad (9)$$

$$CE = 119.349 + 0.223MC - 0.037MS + 1.4 \times 10^{-5}(MC)(MS) - 0.009(MC)^2 + 1.5 \times 10^{-5}(MS)^2 \quad (10)$$

$$TC = 343.831 + 1.059MC - 0.034MS - 1.55 \times 10^{-4}(MC)(MS) + 0.003(MC)^2 + 2.943 \times 10^{-6}(MS)^2 \quad (11)$$

$$MDI = -8.814 + 0.078MC + 0.012MS + 4.7 \times 10^{-5}(MC)(MS) - 0.005(MC)^2 - 4.056 \times 10^{-6}(MS)^2 \quad (12)$$

$$TGL = 63.561 - 5.276MC - 0.014MS - 9.22 \times 10^{-4}(MC)(MS) + 0.192(MC)^2 + 1.1 \times 10^{-5}(MS)^2 \quad (13)$$

$$ICK = -180.022 - 55.429MC + 1.58MS - 0.005(MC)(MS) + 2.173(MC)^2 - 4.95 \times 10^{-4}(MS)^2 \quad (14)$$

Where MC = moisture content % (wet basis); MS = machine speed (rpm); DE = dehusking efficiency (%); TE = threshing efficiency (%); CE = cleaning efficiency (%); TC = throughput capacity (kg/h); MDI = mechanical damage index (%); TGL = total grain loss (%); ICK = input capacity per kilowatt-hour (kg/kWh).

Model F-values for the DE, TE, CE, TC, MDI, TGL and ICK were 4303.29, 183.31, 59.55,  $5.124 \times 10^5$ , 188.39, 367.62 and 150.93 respectively. This indicates that significant models have only a 0.01% chance that an F-value this large could occur due to noise. Model terms that are significant are shown by  $p > F$  less than 0.05 (Table 2). It was observed that moisture content (MC) and machine speed (MS) had significant effect on the performance of the machine for all the model terms considered. Likewise, the remaining model terms were significant for the machine performance indices except for TE and CE where the interaction of moisture content and speed were not significant. Lack of Fit F-values was significant for all the machine performance indices except for DE and TC. This is in line with the findings of Fakayode and Komolafe [20,21].

Table 2. Summary of Analyses of Variance: p-values for the performance indices of the machine

Source	DE P > F	TE P > F	CE P > F	TC P > F	MDI P > F	TGL P > F	ICK P > F
Model	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
A	< 0.0001	0.0011	0.0096	< 0.0001	0.0377	< 0.0001	< 0.0001
B	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0011	< 0.0001
AB	< 0.0001	0.0499	0.9096	< 0.0001	0.0019	0.0016	0.1044
A <sup>2</sup>	< 0.0001	0.9253	0.1288	< 0.0001	< 0.0001	< 0.0001	< 0.0001
B <sup>2</sup>	< 0.0001	< 0.0001	0.0085	< 0.0001	< 0.0001	0.3294	0.0005
Lack of Fit	0.8259	< 0.0001	< 0.0001	0.4904	0.0015	< 0.0001	< 0.0001

$p > F$  less than 0.05 indicates model terms are significant; A, moisture content; B, machine speed; DE, dehusking efficiency; TE, threshing efficiency; CE, cleaning efficiency; TC, throughput capacity; MDI, mechanical damage index; TGL, total grain loss; ICK, input capacity per kWh

### 3.3 Optimization

The plots of predicted values in comparison with experimental values depicts that they are in accordance with each other for all the performance indices determined (Fig. 10 a – g). The optimal values predicted were DE (98.51 %), TE (99.80 %), CE (98.9%), TC (315.80 kg/h), ICK (651.38 kg/kWh), MDI (0.52 %) and TGL (9.1 %) at moisture content of 17.09 % wet basis and speed of 1500 rpm. The value obtained for desirability was 0.714. At these optimal conditions, the experimental values of DE, TE, CE, TC, ICK, MDI and TGL were 98.11 %, 98.14 %, 98.40 % , 311.79 kg/h, 637.06 kg/kWh, 0.50 % and 8.92 % respectively. The difference between the predicted and experimental values was insignificant which points to the fact that the models adopted in predicting the performance indices of the machine were good.

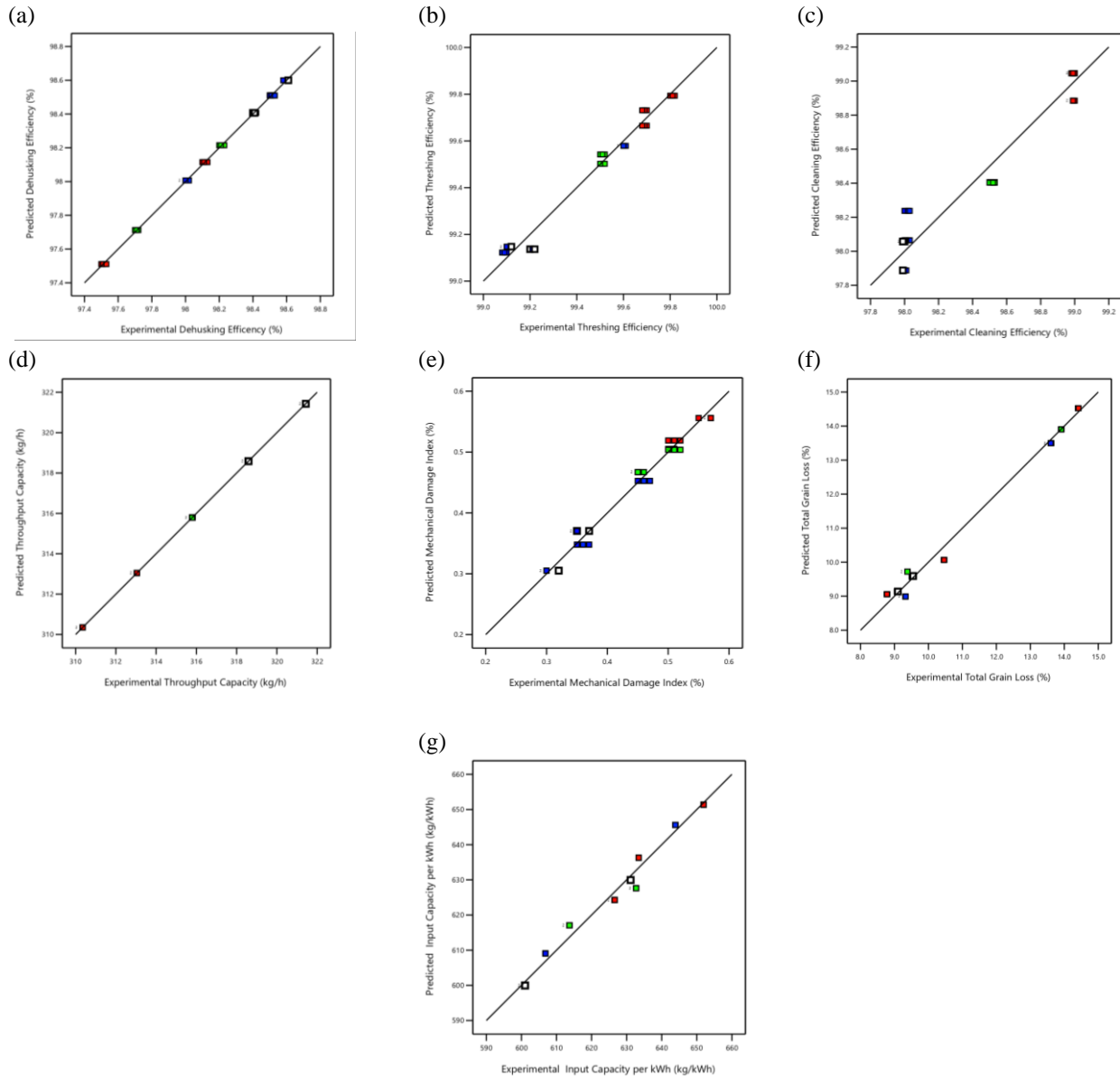


Fig 10. Plots of predicted values against experimental values of the performances indices of the machine (a) dehusking efficiency; (b) threshing efficiency; (c) cleaning efficiency; (d) throughput capacity; (e) mechanical damage index; (f) total grain loss; (g) input capacity per kilowatt-hour.

#### 4. Conclusion

Response surface methodology was used to investigate the effects of moisture content and machine speed on the performance of a designed and constructed maize dehusking and threshing machine. The response surface analysis showed that the moisture content and machine speed had significant effects on the different performance indices (DE, TE, CE, TC, MDI, TGL and ICK). The machine speed was discovered to have greater effects on the response variables than moisture content for the experiments carried out. The effects of moisture content and machine speed were quadratic for all performance indices. The optimization process revealed that the optimal values for the performance indices of the maize dehusking and threshing machine were obtained at the moisture content (17.09 % wet basis) and machine speed (1500 rpm). The optimum values for DE, TE, CE, TC, MDI, TGL and ICK were 98.51 %, 99.80 %, 98.9%, 315.80 kg/h, 0.51 %, 9.1 % and 651.38 kg/kWh respectively. The difference between predicted values and the experimented values was insignificant with minor deviation for all response variables investigated. The mathematical models developed for the DE, TE, CE, TC, MDI, TGL and ICK adequately represent the relationship among variables of the study.

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This research was sponsored by the Author and Co-Authors.

## Ethical Statement

This research does not contain any studies with human or animal subjects performed by any of the authors.

## Conflict of Interest

The authors hereby state that there is no existing conflict of interest.

## Data Availability Statement

Not applicable.

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