



Research Article

Experimental Study and Numerical Analysis of a Melon Seed Shelling Process Based on Response Surface Methodology

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Abstract

Experimentation is fundamental to advancements in science and technology, particularly for optimizing agricultural machinery. This research aims to demonstrate the efficacy of the Design of Experiments (DOE) as a robust methodology in improving the performance of postharvest processing equipment, such as shelling, threshing, and decorticating machines used for postharvest operations in pods, seeds and nuts processing. Using a case study on a melon seed shelling machine, the Response Surface Methodology (RSM) was employed to optimize two key operating parameters: seed moisture content and motor speed after full. A Box-Behnken Design was selected for its efficiency, requiring 13 experimental runs. Analysis of Variance (ANOVA) confirmed the high significance of the developed quadratic model ($F\text{-value} = 50.03$, $p < 0.001$), which exhibited an excellent fit (adjusted $R^2 = 95.33\%$). The results identified optimal parameters: a motor speed of approximately 1920 rpm and a moisture content of 24%, achieving a shelling efficiency of 93%. The second-best configuration yielded a motor speed of 2182 rpm and a moisture content of 22%, resulting in a shelling efficiency of 91%. Verification tests conducted at these optimal settings demonstrated an average relative error of only 0.65%, indicating strong alignment between the predicted and actual outcomes and thus validating the accuracy of the model. These findings confirm that RSM is an effective tool for optimizing the performance and productivity of agricultural machinery in the melon seed industry.

Keywords

Optimization, Full Factorial Design, Box-Behnken Design, ANOVA

1. Introduction

In agricultural processing, relevant activities include operations such as shelling, threshing, dehulling and decorticating [1]. These post-harvest operations are crucial for improving

the value and condition of agricultural materials, particularly in processing pods, seeds, and nuts. Over the years, many technical and engineering schools in Africa have produced

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several machines for these post-harvest operations. However, the adoption of these technologies remains a challenge, with a need for increased mechanisation to enhance agricultural productivity. The benefits of mechanization in agricultural value chains can be summarized as shown in the diagram below, [Figure 1](#). Mechanisation can reduce drudgery, improve efficiency, and lower post-harvest losses, transforming agriculture into a more attractive and profitable sector.

Process optimization of these agricultural processing machines involves studying the effects of various variables influencing the desired response [\[2-4\]](#). This optimization aims to determine the best conditions for achieving optimal machine performance parameters, such as shelling efficiency, separation efficiency, breakage percentage, and machine capacity. Proper experimental design is essential to improve the efficiency and productivity of these machines [\[5\]](#). Experimental

designs like Randomized Complete Block Design are widely used in agricultural experiments to control variability [\[6\]](#). There are several factors that are considered significant in maximizing the efficiency and profitability of most post-harvest processes agricultural machinery, which can be categorized into crop condition, operational and design parameters. Crop condition factors are the physical properties or characteristics of the crop that affect machine performance. These include moisture content, crop maturity, size, species and variety. Design or machine factors, are the factors that determine the configuration and geometry of the working mechanism of a machine. Operating parameters are factors that affect the performance of a machine during a process or an activity and include feed rate, operating speed, and clearance [\[7\]](#).

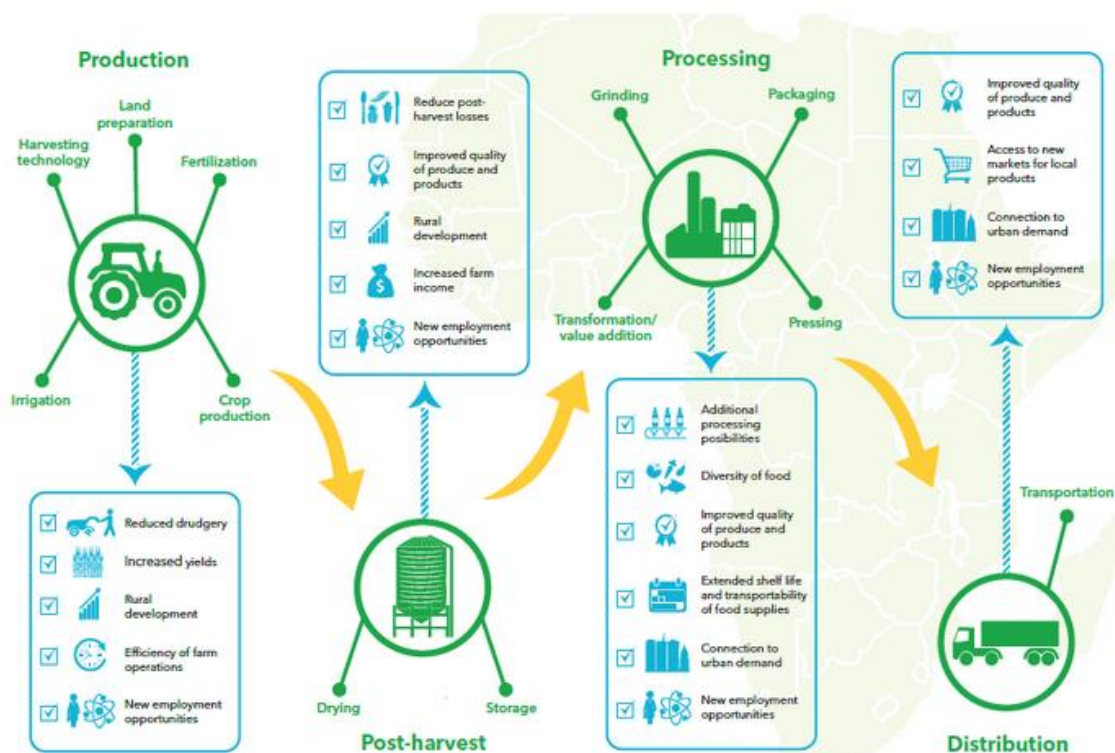


Figure 1. Benefits of mechanization along the agricultural value chains [\[2\]](#).

The success of any shelling, threshing, dehulling or decortication process optimization depends on experimental testing and statistical analysis. To stay ahead and beat the business competition, engineers and scientists must move from the old-fashioned one-factor-at-a-time strategy, usually taught at universities and still widely practiced by companies to statistical approaches to DOE that are far superior to one-factor-at-a-time. Unfortunately, training in advanced statistical concepts and methods, including hypothesis testing, experimental design, and hands-on analysis of experimental data using com-

putational software, is not a regular part of engineering qualification in Cameroon as in most countries. DOE can help the engineer/scientist to determine appropriate settings for factors that optimize the machine performance. RSM is a widely used tool within DOE for modelling and optimizing food processes [\[8, 9\]](#). RSM is suitable for evaluating the effects of independent variables and their interactions on the responses.

Since engineers and scientists perform experimental analysis as an integral part of their work, regardless of whether they have studied statistics, the aim of this paper was to emphasize the relevance of systematically applying DOE as a reliable

method for analysing complex interactions arising from crop factors, machine and operational factors, and for ensuring efficient performance of agro-industrial equipment. The following sections of the literature review present more information on the types of DOE techniques, their advantages over the traditional experimental methods. This is followed by a review of the factors influencing the shelling, threshing, dehulling and decortication processes. Finally, the results of the assessing of the effect of moisture content and motor speed by using the RSM are presented to provide practical insights into the use of DOE in process optimization.

2. Review of Some Related Works

DOE involves systematic methods for planning, conducting, and analyzing experiments to understand how multiple factors influence a particular response [10]. It is a structured approach to efficiently explore the relationship between input variables and output responses, enabling researchers to identify optimal conditions and improve process performance [11]. Among these techniques, RSM is a valuable tool for modeling and analyzing relationships between input variables and outputs, especially when dealing with complex, nonlinear relationships [12]. RSM is particularly useful in agricultural and food sciences for optimizing processes and product formulations [9].

RSM includes a range of sophisticated DOE techniques that are effective for modeling the connections between process variables and their outputs. This methodology is particularly beneficial for enhancing models that exhibit curvature in their response surfaces. RSM utilizes mathematical and statistical approaches to create empirical models, assess the influence of different inputs, and identify optimal conditions. Since its introduction by Box and Wilson in 1951, RSM has gained widespread adoption among researchers and engineers seeking to optimize parameter settings for improved processes and equipment designs [13, 14].

RSM has long been a reliable approach for optimization based on experimental design, finding applications across numerous research domains. Over 48,000 papers indexed in Sco-

pus have utilized this methodology. The engineering disciplines are the primary users of RSM, followed by fields such as chemical engineering, chemistry, biological sciences, and various applied sciences [15]. In Africa, RSM has been applied to optimize various agro-industrial processes, such as the production of complementary foods and the optimization of cassava yield [16, 17].

RSM is particularly useful when the relationship between factors and responses is nonlinear and when curvature in the response surface is suspected. This makes it suitable for exploring optimal operating conditions across multiple variables, especially after preliminary experiments indicate significant interactions or nonlinearities. In contrast, Full Factorial Design and the Taguchi Method serve different purposes. Full Factorial Design is ideal for comprehensively exploring all possible factor combinations, providing detailed insights into interactions but can become impractical with many factors due to the exponential increase in required runs. The Taguchi Method focuses on robust design and variation reduction, emphasizing control over noise factors to ensure consistent performance. It is particularly useful in early-stage experimentation to identify key factors without deeply exploring their interactions [18]. However, Taguchi may be less accurate than RSM techniques like Box–Behnken Design and Central Composite Design for optimization [19].

Central Composite design and Box-Behnken Design are two common types of RSM used for experimentation. Box-Behnken Design is particularly effective for non-sequential experiments and offers a robust design that ensures all factors remain within the region of interest. In contrast, Central Composite Design typically necessitates a larger number of experiments and may involve extreme settings that exceed safe operational limits.

While Box-Behnken Design requires three levels for each factor, with treatment combinations positioned at the mid-points of the experimental space and at the centre, it also benefits from needing fewer experimental runs compared to Central Composite Design. Both Central Composite Design and Box-Behnken Design allow for efficient estimation of linear, quadratic, and interaction effects.

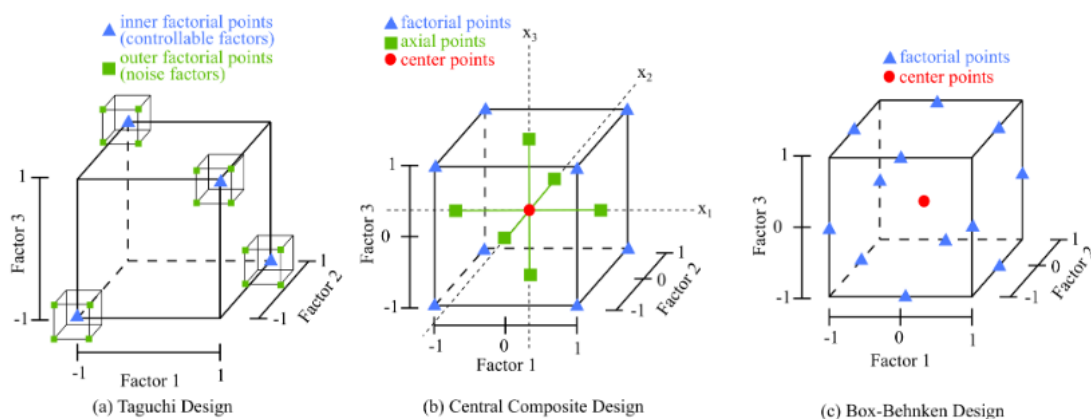


Figure 2. Graphical representation of the 3-factor design space for the different RSM designs [20].

In the article by Botha et al. [20], design point locations for Central Composite Design, Box-Behnken Design, and Taguchi designs differ visually within a three-factor cubic space, as shown in Figure 2, with Taguchi forming clustered factorial layers, Central Composite Design spreading across vertices and faces, and Box-Behnken Design concentrating on edge midpoints. Taguchi designs use crossed arrays to form clustered factorial layers, with inner arrays for control factors and outer arrays for noise factors, creating paired combinations across levels that emphasize robustness over higher-order interactions [21], without center or axial points. In contrast, Central Composite Design distributes points at the cube's vertices, includes axial points at the centres of each face, and incorporates a central point, establishing a five-level setup that facilitates quadratic modelling. Box-Behnken Design positions points along the midpoints of the cube's edges and includes a centre point, omitting vertices entirely, resulting in an efficient design tailored for modelling quadratic surfaces. These design principles and their practical implementations in manufacturing experiments are further elaborated in Astakhov's foundational chapter on design of experiment methods [22].

Several studies emphasize distinctions between different RSM designs. For example, a comparative analysis of Taguchi, Box-Behnken Design, and Central Composite Design showed that while the Taguchi method is more cost-effective due to fewer experimental runs, Box-Behnken Design and Central Composite Design offer more accurate optimization results

[23]. Another study highlights that RSM is a mixture of regression analysis and experimental designs meant for response optimization, suitable for non-linear relationships between parameters [19]. The Taguchi method is used to reduce the number of treatment combinations [24].

A comparative analysis showed that while the Taguchi method is more cost-effective due to fewer experimental runs, Box-Behnken Design and Central Composite Design, both RSM techniques, can offer more accurate optimization results [25]. In cases where the relationship between parameters does not follow a linear pattern, RSM is more suitable than factorial designs [26]. The Taguchi method is often used to reduce the number of treatment combinations.

3. Materials and Methods

The seed sheller used in this study was powered by a 4.5 horsepower gasoline engine, with a production capacity of approximately 50 kilograms per hour. Its major components included the hopper, shelling chamber, separation chamber, and gasoline engine, all securely mounted on a sturdy frame.

3.1. Sheller Structure and Components

Most melon seed shellers as depicted in Figure 3, share these basic components [27]:

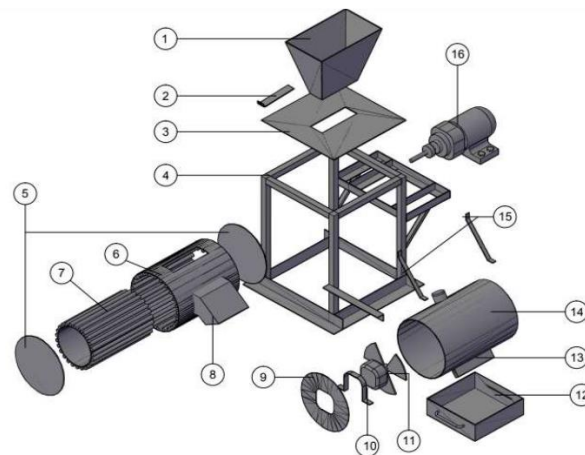


Figure 3. Sketch and line diagram of the melon sheller [27]: 1 – Hopper; 2 – sight glass; 3 – Frame cover; 4 –Housing frame; 5 – Disc cover; 6- Shelling drum; 7- Shelling disc; 8- Outlet for shelled melon for melon; 9- Blower guide; 10- Guide; 11- Fan; 12- Outlet plate; 13- Blower outlet; 14-Blower; 15- Hub support; 16- Electric mower.

- 1) *Hopper*: A funnel-shaped inlet for feeding melon seeds into the machine. It's designed to ensure a smooth flow of seeds into the shelling unit.
- 2) *Housing frame*: Provides the main support for all other components. Typically made of mild steel angle iron or hollow tubes.
- 3) *Shelling Chamber/Unit*: The core of the machine where the shelling action occurs. This unit's design varies significantly across different machines. Common elements include:
- 4) *Rotating disc with vanes*: A rotating component that impacts or rubs the melon seeds to remove the shell. Vanes

or blades are often attached to the disc to enhance the shelling action.

- 5) *Stationary drum*: A stationary surface against which the seeds are thrown or rubbed by the rotating impeller. Some designs incorporate slots or grooves on this surface to aid in shelling.
- 6) *Power System*: Usually, an electric motor or gasoline engine that provides the rotational force for the shelling mechanism. Some machines use gasoline engines. Power is transmitted via belts and pulleys.
- 7) *Separation unit*: Some machines include a separation unit to separate the shelled seeds from the husks. This often involves a blower or fan to use air to separate the lighter husks from the heavier seeds.
- 8) *Delivery outlets*: Directs the separated seeds and husks out of the machine.

3.2. Working Principle

The primary working principle involves applying force to the melon seeds to crack the shell and separate it from the kernel. Different machines achieve this in slightly different ways:

- 1) *Impact force*: Many machines use impact force, where the seeds are thrown against a hard surface or impacted by a rotating component [28]. The energy absorbed beyond the elastic limit of the melon seeds causes the shell to crack.
- 2) *Rubbing/Attrition*: Some designs use a rubbing action between a rotating disc and a stationary surface to shear the shell off the seed [27].
- 3) *Extrusion*: Some machines use the principle of extrusion.
- 4) *Bending*: Some machines feed the melon seeds through sets of rollers having ridges on their surfaces.

3.3. Parameters Affecting Performance

Preliminary research was conducted to identify the significant parameters on shelling efficiency. Factors that influence the efficiency and performance of melon seed shellers include:

- 1) *Moisture content of seeds*: Moisture content significantly affects shelling efficiency and seed damage [29]. Optimum moisture levels soften the shell, making it easier to remove without damaging the kernel. A study on a

centrifugal melon shelling and cleaning machine found that shelling efficiency decreased with an increase in seed moisture content from 15% to 25%, while other studies suggest an optimal moisture content of around 18% for melon seeds [30].

- 2) *Shelling speed/Motor speed*: The speed of the rotating components affects the impact force or rubbing action. Too high a speed can cause seed breakage, while too low a speed may not effectively shell the seeds. Some studies indicate an optimal speed range for maximizing shelling efficiency while minimizing damage [27].
- 3) *Machine design*: The design of the shelling chamber, the type of impellers or discs used, and the clearances between moving and stationary parts all play a crucial role. The principle of operation (e.g., impact, friction, extrusion) also influences performance. Key design considerations include ease of fabrication, availability of materials, cost-effectiveness, and power requirements [30].
- 4) *Feed rate*: The rate at which seeds are fed into the machine can affect efficiency [31]. An optimal feed rate ensures that the machine is neither overloaded nor underutilized.
- 5) *Variety of melon seed*: Different varieties of melon seeds have different physical properties (size, shape, hardness), which can affect how they respond to the shelling process [32]. Some varieties are more easily shelled by machines, while others are better suited for manual shelling [33].
- 6) *Number of beaters*: The number of beaters in a centrifugal melon shelling machine also affects its cleaning and recovery efficiency.
- 7) Shelling speed and moisture content were identified as key factors likely to affect the breakage percentage of melon seeds [34].

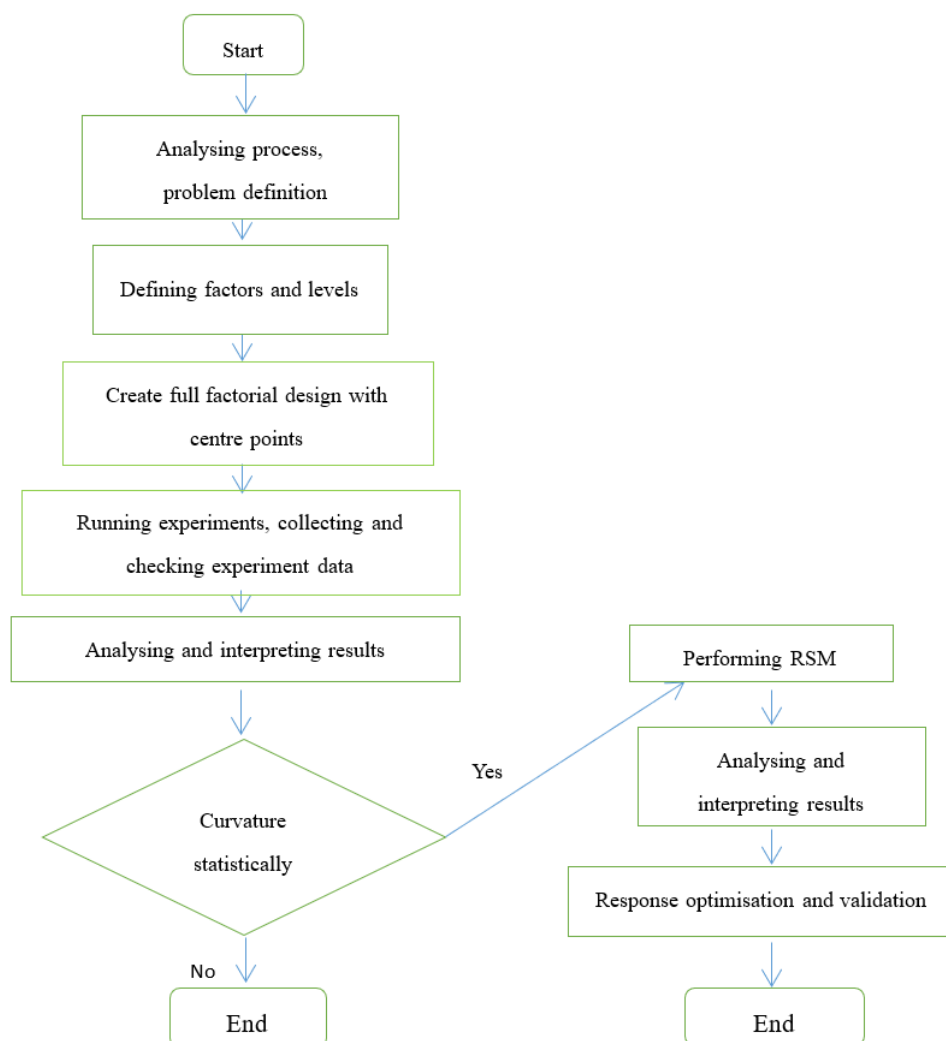
RSM using a Box-Behnken Design was implemented using MINITAB statistical software, with two primary goals. The first was to determine the optimal settings for minimizing dimensional error. The second was to investigate the relationship between the factors and responses to better understand the system. The steps involved in applying RSM are illustrated in Figure 4.

Table 1. Factors and levels.

Factor	Lower level (corner point)	Medium (Centre point)	High level (corner point)
Motor speed (rpm)	900	1500	2100
Moisture content (%)	14	20	26

Table 2. Runs in standard order.

Runs	MR (rpm)	MC (%)
1	1	1
2	1	1
3	-1	-1
4	-1	-1
5	-1	1
6	-1	1
7	1	-1
8	1	-1
9	0	0
10	0	0
11	0	0

**Figure 4.** RSM flow chart.

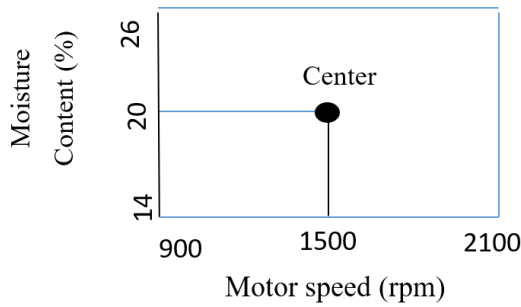


Figure 5. Two factors two levels full factorial design with centre point.

A 2x2 full factorial design with centre points was employed to model the relationship between the factors and the response (Figure 5, Tables 1, 2). The experiment was run in a completely randomized manner. The corner points were replicated twice, and three centre points were added per block, providing six degrees of freedom for the error term (Table 2). The centre points were used to check for curvature in the response; if significant curvature was detected, a RSM approach would be warranted. As detailed in Table 2, the high, centre, and low values of each factor were coded as +1, 0, and -1, respectively, and a response was measured for each experimental run.

RSM was used to build a regression model from the experimental data, representing the relationship between the factor variances and the response shift. The adequacy of this model and the significance of the control parameters and their interactions on shelling efficiency were then determined through ANOVA implemented using MINITAB. This approach is well-established, as demonstrated by its successful application in similar studies for analysing the influence of experimental parameters on performance characteristics [35].

3.4. Determination of Moisture Content

The seed moisture content of the seeds was obtained by soaking a large quantity of melon seeds for 12 hours to ensure that the seeds absorbed all the moisture. The seeds were then sun-dried in a thin layer. The moisture contents MC (%) were obtained by taking samples from the drying batch.

$$MC(\%) = \frac{M_{bd} - M_{ad}}{M_{bd}} \quad (1)$$

Where

M_{bd} = Mass before drying

M_{ad} = Mass after drying

To obtain samples with higher moisture contents, the amount of water was to be added to obtain the desired moisture content was a calculated using the formula:

$$M = M_s \times \frac{MC_2 - MC_1}{100 - MC_2} \quad (2)$$

Where

M = Amount of water to add (kg)

M_s = Mass of sample (kg) to be introduced into the machine (kg)

MC_1 = Initial moisture content (%)

MC_2 = Final moisture content (%)

Determination of shelling efficiency

Seed shelling efficiency (η_e) was calculated by using Eq (3).

$$\eta_e = \frac{M_{cuc} + M_{cbc}}{M} \times 100 \quad (3)$$

Where

M_{cuc} = Mass of clean unbroken cotyledon in product collected at outlet chute (Kg)

M_{cbc} = Mass of clean broken cotyledon in product collected at outlet chute (kg)

M = Total mass of seed fed through the machine's hopper (Kg)

4. Results: Analysis and Discussion

4.1. Centre Points Factorial Design Results and Data Analysis

A known quantity of melon seeds was processed using the shelling machine, with the experimental variables detailed in Table 2. The resulting shelling efficiency for each run is presented in Table 3.

Table 3. The result of shelling efficiency in standard order.

Runs	MR (rpm)	MC (%)	SE (%)
1	1	1	95.9
2	1	1	96.5
3	-1	-1	54.1
4	-1	-1	55.7
5	-1	1	73.58
6	-1	1	73.95
7	1	-1	75.3
8	1	-1	75.9
9	0	0	86,12
10	0	0	86,96
11	0	0	86,45

4.1.1. ANOVA Analysis

In this section, we statistically evaluate whether motor

speed, moisture content, and their interaction significantly affect shelling efficiency, similar to previous studies [36, 37]. ANOVA was conducted using MINITAB, and the results are presented in Table 4. In ANOVA, the F-statistic is used to determine the significance of the model terms; a larger F-value indicates a greater probability that the effect is statistically significant. As shown in Table 4, there was no significant impact of the interaction between motor speed and moisture content on shelling efficiency ($p > 0.05$). However, the effects of motor speed, moisture content and curvature were all statistically significant on shelling efficiency ($p \leq 0.05$). The absence of a significant interaction between motor speed and moisture content implies that the impact of each factor on the shelling efficiency is independent of the other. This implies that optimising motor speed and moisture content can be done separately, without considering their combined effect. This finding is consistent with some studies in which the individual effects of these parameters are more pronounced than their interaction.

Table 4. ANOVA of the impact motor speed and the moisture content.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	0,199	0,050	1447,13	0,000
MR	1	0,093	0,093	2700,93	0,000
MC	1	0,078	0,078	2260,89	0,000
MR $\times$ MC	1	0,000	0,000	4,37	0,082
Curvature	1	0,028	0,028	822,31	0,000
Error	6	0,000	0,000		

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Total	10	0,200			

The significant main effect of motor speed is consistent with research showing that optimal speed is crucial for efficient threshing or shelling. Insufficient speed may not provide sufficient force for effective separation, while excessive speed can lead to grain damage and reduced efficiency [38]. Similarly, the significant main effect of moisture content corroborates the finding that moisture levels critically influence the mechanical properties of grains, affecting their resistance to shelling and susceptibility to damage [39].

The significance of the curvature term from the ANOVA analysis indicates a non-linear relationship between the factors and the response, suggesting that optimal conditions are not simply at the extremes of the tested ranges but rather at specific points within them [40]. The curvature's significance underscores the necessity of utilizing appropriate experimental designs, such as Central Composite Design or Box-Behnken Design, which are specifically formulated to effectively model and optimize these complex processes [41].

4.1.2. Residual Plots

Based on the ANOVA results, a regression model was developed to predict the response (shelling efficiency) in relation to different motor speed and melon seed moisture content values.

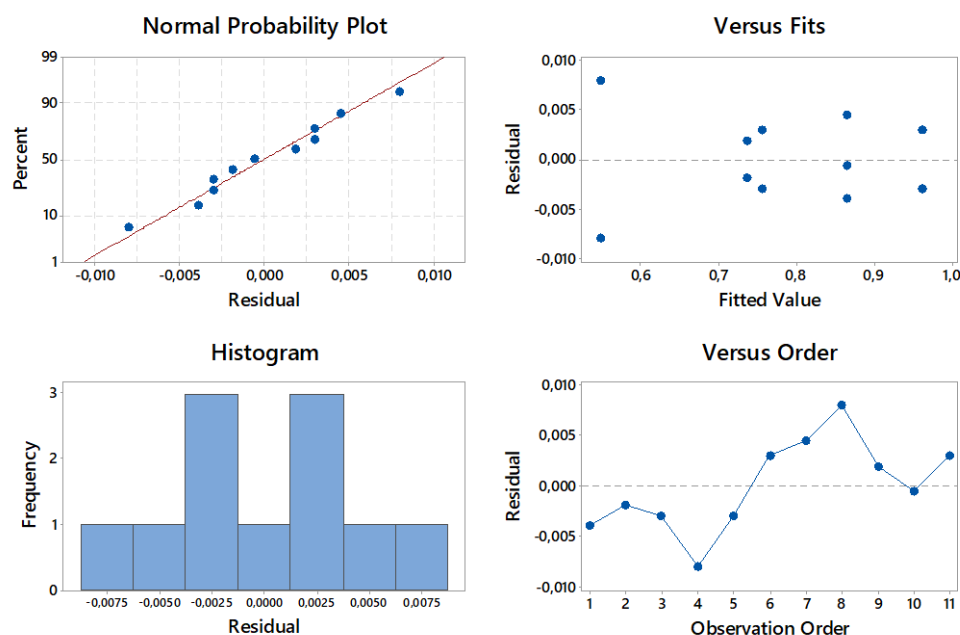


Figure 6. Residual plot for shelling efficiency.

The validity of the model was assessed using the residual plots shown in Figure 6. In the normal probability plot, the residuals closely follow the straight line, indicating that there is no significant deviation from normality. The residuals versus fitted values plot shows points scattered randomly around zero with no obvious pattern, indicating homoscedasticity and the absence of outliers. However, the histogram of the residuals deviates from a bell-shaped curve, suggesting a departure from normal distribution. Conversely, the plot of residuals versus observation order exhibits no discernible trend, confirming the independence of the residuals.

While the normal probability plot supports normality, the histogram highlights the importance of using multiple diagnostic tools for model validation, especially since histograms can be sensitive to bin width and sample size. These apparent contradictions underscore the necessity of employing RSM, which offers a systematic approach to explore and optimize the non-linear relationships among motor speed, moisture content, and shelling efficiency, thereby enhancing the robustness of the predictive model.

4.1.3. Main Effects Plot

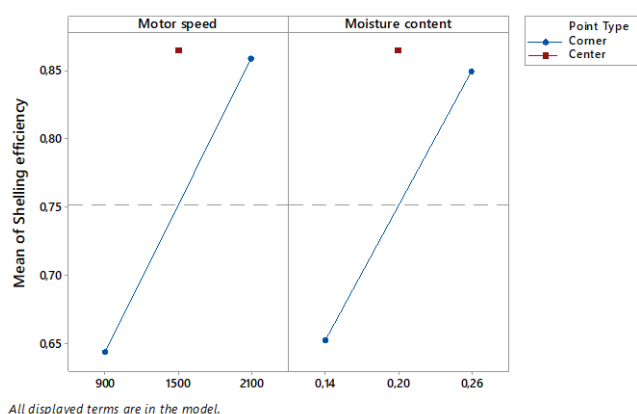


Figure 7. Main effects plots for shelling efficiency.

After developing a regression model based on the ANOVA results to predict shelling efficiency in relation to motor speed and melon seed moisture content, a main effects plot analysis was conducted to further understand the individual contributions of each factor. The main effect plot in Figure 7 shows that increasing the motor speed from 900 rpm to 2100 rpm has a stronger effect on shelling efficiency than varying the moisture content, as demonstrated by the steeper slope of the line for the motor speed. This suggests that, within the tested range, motor speed is a more critical factor for optimising shelling efficiency. Studies on corn shellers and other agricultural processing equipment have similarly found that operating speed significantly impacts performance [42]. Furthermore, the significant disparity between the centre point and the endpoints

of the effect lines indicates curvature in the model. This indicates that the relationship between the factors and the response is not linear, suggesting that there may be an optimal combination of factor levels within the experimental region. As this curvature effect was statistically significant, a RSM experiment was conducted to fit a second-order model. Second-order models are commonly used in RSM to approximate the response surface when curvature is present, providing a more accurate representation of the relationship between the factors and the response. Using a second-order model is therefore justified by the need to capture non-linear effects and optimise the process effectively.

4.2. Response Surface Experiment: Results and Data Analysis

Shelling experiments were conducted using a known quantity of melon seeds and the parameters defined by a RSM design. A Box-Behnken Design was selected for three control factors due to its higher efficiency compared to a Central Composite Design [43]. While a Central Composite Design with a comparable number of factors would require 20 runs (8 factorial, 6 axial and 6 centre points), the Box-Behnken Design can perform the analysis with just 13 base runs, including a single replicate and block. The experimental matrix, detailed in Table 5, was executed, and the resulting shelling efficiency for each run is presented in standard order in the same table. The shelling experiments were conducted using a known quantity of melon seeds and the parameters were defined by a RSM design. While a comparable Central Composite Design requires 20 runs (8 factorial, 6 axial, 6 centre points), the Box-Behnken Design accomplishes the analysis in 13 base runs with a single replicate and block. BBDs are particularly useful when the experimental region has constraints, and extreme points are to be avoided. Box-Behnken Designs are also known for requiring fewer runs than Central Composite Designs for the same number of factors, making them more resource-efficient.

Table 5. Box-Behnken Design results for shelling efficiency across different factor levels.

Runs	MR (rpm)	MC (%)	SE (%)
1	2100	26	96,5
2	2100	14	75,3
3	900	14	54,1
4	900	26	73,58
5	651,5	20	58,89
6	2348,5	20	82,49
7	1500	11,5	58,74

Runs	MR (rpm)	MC (%)	SE (%)
8	1500	28,5	82,65
9	1500	20	86,52
10	1500	20	86,29
11	1500	20	85,54
12	1500	20	86,77
13	1500	20	86,96

The experimental matrix, detailed in Table 5, was executed, and the resulting shelling efficiency for each run is presented in standard order in the same table. The choice of Box-Behnken design is consistent with studies that prioritise efficiency and safety in experimental designs.

4.2.1. ANOVA Analysis of Box-Behnken Design

ANOVA analysis conducted using MINITAB and presented in Table 6 revealed that the interaction between motor speed and moisture content had no statistically significant impact on shelling efficiency ($p = 0.771 > 0.05$). All other model terms were significant. The overall model proved significant, indicated by an F-value of 50.03 and a p-value of < 0.001 . However, a significant lack of fit ($p = 0.001$) was identified, suggesting that the model does not adequately capture the complexities of the data. This lack of fit indicates that the relationship between motor speed and moisture content may not be fully represented, potentially overlooking how these factors interact to influence the shelling mechanism. For instance, while motor speed can enhance shelling efficiency, inappropriate moisture levels may lead to seed damage or ineffective shell removal, emphasizing the need for a more nuanced model. The probability of observing an F-value of this magnitude due to random noise is only 0.1%, indicating that the issues affecting fit are systematic rather than random. The pure error reflecting the variability of replicates at the center points had a mean square of 0.000122, corresponding to a standard deviation of 0.000030, reinforcing the variability in seed behavior under different processing conditions.

Table 6. ANOVA of Motor Speed and Moisture Content in Box-Behnken Design.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0,202	0,040	50,03	0,000

Source	DF	Adj SS	Adj MS	F-Value	P-Value
MR	1	0,075	0,075	93,10	0,000
MC	1	0,069	0,069	86,03	0,000
MR × MR	1	0,032	0,032	40,11	0,000
MC × MC	1	0,032	0,032	40,08	0,000
MR × MC	1	0,000	0,000	0,09	0,771
Error	7	0,006	0,001		
Lack-of-Fit	3	0,006	0,002	60,59	0,001
Pure Error	4	0,000	0,000		
Total	12	0,207			

4.2.2. Analysis of Box-Behnken Design Model Results

The model summary statistics of Box-Behnken Design quadratic regression model are presented in Table 7.

Table 7. Box-Behnken design model results.

Term	S	R-sq	R-sq (Adj)	R-sq (Pred)
Values	0,028	97,28%	95,33%	80,97%

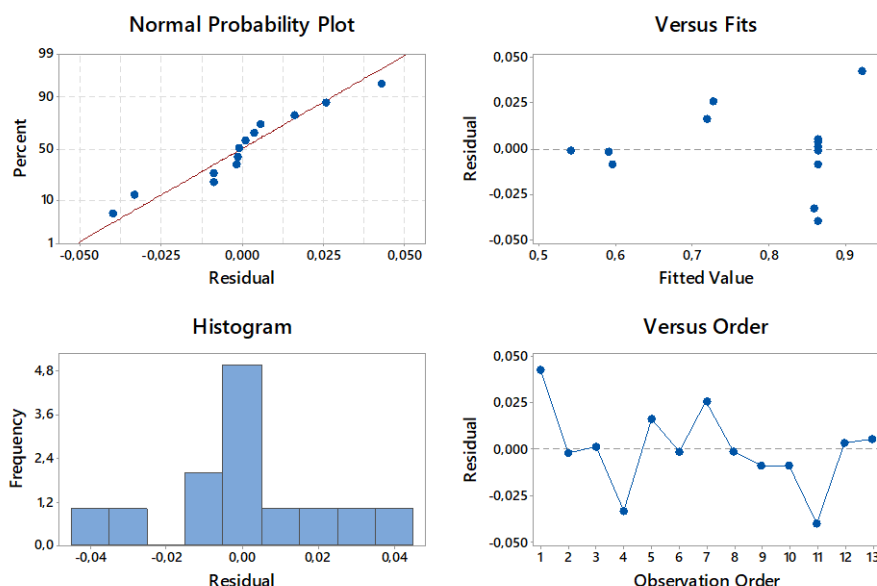
The standard deviation of the residuals (S) is 0.0283957. The R^2 value of 97.28% indicates that the model explains a high proportion of variance in shelling efficiency, with values closer to 1.00 being ideal. The adjusted R^2 value of 95.33% confirms that the model accounts for a significant amount of response variability. However, the predicted R^2 at 80.97% suggests potential over fitting, indicating the model may have limited predictive capability for new observations.

The non-significant interaction between motor speed and moisture content was removed to enhance model performance. This adjustment is crucial, as optimizing these two factors separately can lead to better shelling outcomes: higher motor speeds improve the efficiency of shell removal, while optimal moisture levels help maintain seed integrity and minimize damage. The results for the refined model are shown in Table 8, where the adjusted R^2 and predicted R^2 values demonstrate reasonable agreement, indicating a more robust model that better represents the relationship between the factors and shelling efficiency.

Table 8. Optimised Box-Behnken design model results.

Term	S	R-sq	R-sq (Adj)	R-sq (Pred)
Values	0,027	97,24%	95,86%	86,94%

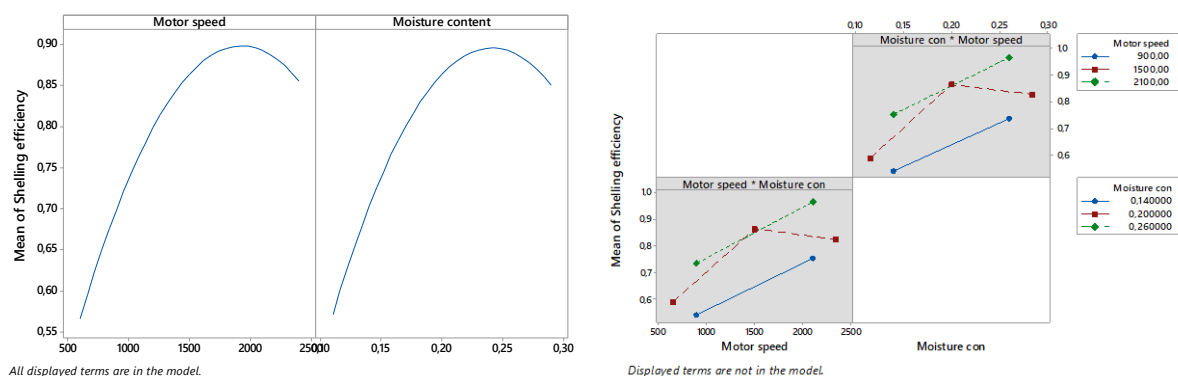
4.2.3. Analysis of Box-Behnken Design Residual Plots of Shelling Efficiency

**Figure 8.** Residual plot for shelling efficiency.

The residual plots in Figure 8 were examined to validate the model's assumptions. In the normal probability plot, the residuals adhere closely to the straight line, supporting the assumption of normality. The plot of residuals versus predicted values shows a random scatter of points above and below zero with constant variance, indicating homoscedasticity and the absence of outliers. Finally, the plot of residuals versus observation order reveals no discernible pattern, confirming that the residuals are independent and that no systematic bias is present in the model's predictions. Thus, then nonlinear regression model is appropriate for the data.

4.2.4. Main and Interaction Effects Plot for Box-Behnken Design

The main effects plots in Figure 9 (left) show clear curvature for both motor speed and moisture content, indicating a non-linear relationship between these factors and the response. This non-linearity is consistent with the interaction effect observed in the corresponding plots in Figure 10 (right).

**Figure 9.** Main effects and interaction plots.

4.2.5. Contour Plots and Surface Plot

The response surface and contour plots in the figures below visualise the predicted model equation, illustrating the effect

of the two variables on efficiency yield. The contour plot, in particular, clearly shows the non-linear relationship between motor speed and moisture content.

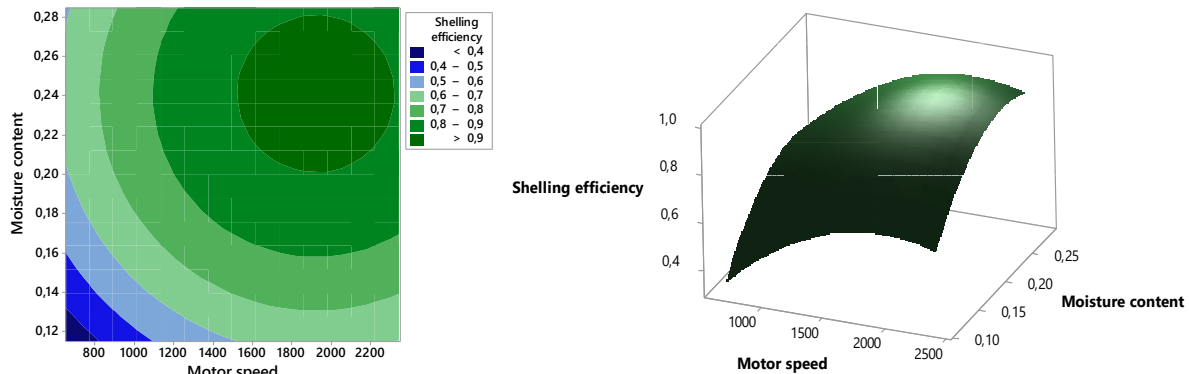


Figure 10. Contour plot (left) and surface plot (right).

4.2.6. Shelling Efficiency Optimisation

This stage of the analysis focused on numerical optimization to maximize the shelling efficiency. The optimization procedure utilized the fitted quadratic model derived from the Box-Behnken Design, with the factor levels constrained to the experimental ranges presented in Table 9 to ensure practical applicability. The design expert MINITAB Software iterated over all the ranges of factors and found the maximum yield shown below in Table 10.

The design expert MINITAB Software iterated over all ranges of factors to identify the maximum yield, as detailed in Table 10. The results showed that the optimal solution for motor speed was approximately 1920 rpm, with a moisture content of 24%, achieving a shelling efficiency of 93% and a composite desirability of 0.607. This solution demonstrated the highest efficiency among all evaluated parameters. The second-best configuration provided a motor speed of 2182 rpm and a moisture content of 22%, yielding a shelling efficiency of 91% with a lower composite desirability of 0.229. The varied results highlighted the importance of optimizing both motor speed and moisture content to achieve maximum efficiency.

Table 9. Optimisation constraints.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight
MS	in range	900	2100	1	1
MC	in range	0,14	0,26	1	1
SE	maximize	0,9	0,965	1	1

Table 10. Optimisation results.

Solution	MS (rpm)	MC (%)	SE (%)	CD
1	1920,0	24,0	93,0	0,607
2	2182,0	22,2	91,1	0,229
3	1646,2	26,0	90,9	0,172
4	1660,8	26,2	90,8	0,168
5	1572,0	25,3	90,4	0,076

4.3. Verification Test

To verify the accuracy of the prediction model, the melon seed shelling equipment was operated under the suggested optimal condition of 93.0% shelling efficiency. A comparison between the optimized value and the results from the verification tests is presented in Table 11, which includes five sets of validation experiments.

Table 11. Comparison of predicted value and verification test value.

Test	ESE (%)	PSE (%)	Error
1	91.5	93,0	1,61
2	92.0	93,0	1,08
3	92.8	93,0	0,22
4	93.5	93,0	-0,54
5	92.2	93,0	0,86

Test	ESE (%)	PSE (%)	Error
Average	92,4	93	0,65

As shown in Table 11, the average relative error in shelling efficiency based on the optimal parameters was 0.65%. This indicates that the optimal solutions obtained from the predicted model using the Box-Behnken Design closely matched the verification test results. The findings confirm that the optimization was both accurate and effective, demonstrating the efficiency of the Box-Behnken Design in enhancing shelling quality.

5. Conclusions

This study successfully optimized the melon seed shelling process using DOE with MINITAB, specifically assessing the impacts of motor speed and moisture content on shelling efficiency. Analysis of the full factorial experiments indicated a significant disparity between the center point and the end-points of the effect lines, revealing curvature in the model and suggesting a non-linear relationship between the factors and the response variable. Utilizing a Box-Behnken design, selected for its operational efficiency, the study identified optimal parameters of approximately 1920 rpm for motor speed and 24% for moisture content, achieving a shelling efficiency of 93%. Verification tests performed at the optimal settings confirmed an average relative error of only 0.65%, indicating a close alignment between predicted and actual outcomes, thereby validating the model's accuracy.

This research highlights the significance of selecting appropriate DOE methodologies tailored to specific study objectives, available resources, and system complexity, demonstrating that RSM is an effective tool for enhancing agricultural machinery design. The preference for a Box-Behnken Design over a Central Composite Design was substantiated by its efficiency in requiring fewer experimental runs while effectively capturing the system's significant curvature. Overall, this study contributes valuable insights that could enhance the efficiency and profitability of the melon seed industry.

Abbreviations

MR	Motor Revolution
MC	Moisture Content
SE	Shelling Efficiency
ESH	Experimental Shelling Efficiency
PSE	Predicted Shelling Efficiency
CD	Composite Desirability

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Conflicts of Interest

The authors declare no conflicts of interest.

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