Optimization of Process Variables of a Newly Developed Vertical Palm Fruit Digester as it Affects the Weight of Digested and Undigested Fruits

[1]Alexander Aniekan Offiong, [2]Philip T. Aondona, [1]Emmanuel. U. Odeh, And [1]A. P. Ihom

[1]Department of Mechanical and Aerospace Engineering, Faculty of Engineering, University of Uyo-Nigeria.

[2]Department of Industrial Engineering, Durban University of Technology (Dut) Durban-South Africa.

DOI: https://doi.org/10.51244/IJRSI.2026.1307000305

Received: 31 July 2026; Accepted: 05 August 2026; Published: 16 August 2026

ABSTRACT

This work has conducted a study on the 'Optimization of Process Variables of a Newly Developed Vertical Palm Fruit Digester as it affects the Weight of Digested and Undigested Fruits'. The optimization analysis of the palm fruit digester utilized three factors (speed, initial palm fruit weight, and number of blades) and the targeted responses were digested and undigested weight of palm fruits. The results obtained from the work showed that, the weight of digested fruit (Wd) response surface analysis showed that the model had a high significance ($F = 86.63$, $p < 0.0001$), thus indicating high predictive ability and a good fit. The weight of palm fruit at the start of the growth period (B) showed the strongest influence with a coefficient of 2.51 and very significant p-value (< 0.0001), hence, it proved to be the decisive influence of Wd. The weight of undigested fruit (Wu) response analysis revealed that the model lacked statistical significance on average ($F = 3.05$, $p = 0.0888$) and thus this response exhibits less predictive power relative to others. But among the factors used, the factor weight of palm fruit (Wi) turned out to be the main determinant, with a coefficient estimate of 0.49 and a very significant effect ($p = 0.001$). The work showed that the quadratic model of the weight of digested palm fruit is highly significant ($F=86.63$, $p<0.0001$) and that the vertical palm fruit digester can be accurately predicted with Response Surface Methodology (RSM). The weight of undigested fruit (Wu) ANOVA, proved that the general model was not significant ($F = 3.05$, $p = 0.0888$). The data showed a low predictive power in comparison with other responses. It is evident in the plot that the initial weight of palm fruit (Wi) has the most significant effect, which agrees with the result of the ANOVA, that only the wi (initial weight of palm fruit) had any significant effect ($p < 0.0001$). The ANOVA results are validated by the visualization, indicating that the initial weight of palm fruit (Wi) is the most significant variable. When Wi is raised, the quantity of undigested residue will correspondingly increase with contour gradients illustrating the positive linear association and finally based on Response Surface Methodology (RSM), the desirability plot describes the optimum operating point of the vertical palm fruit digester to achieve maximum efficiency (ŋ), digesting capacity (Dc) and minimum weight of undigested fruit (Wu), with weight of digested fruit (Wd) generated being a balanced output. The best settings: speed (A) of 595.873 RPM, starting weight B (Wi) of 5.472 kg and 6 blades (C)- resulting in Wd = 4.866 kg, Wu = 0.605 kg, Tn =1.095 min, Dc = 289.300 kg/h, n = 90.200 percent and viscosity = 0.048 Pa.s with a desirability of 1.000.

Keywords: Optimization; Digested weight; Palm fruit; Undigested weight; Initial weight; Vertical palm fruit digester.

INTRODUCTION

Machines with palm oil mill process include: palm fruit sterilizer, palm fruit thresher, palm fruit digester, palm oil press machine, palm kernel cracker, palm kernel separator machine and palm kernel oil expeller machine. Researchers across the world believe that the development of machines to be used in oil palm mills is of utmost importance. Much has been focused on the creation of palm kernel oil production machines. This work is focused on palm oil production, and of particular interest the development of a vertical palm fruit digester for digestion and extraction of palm oil at optimized conditions (Aniekan, 2025).

Previous works have developed machines such as palm kernel crackers, palm kernel separator, and palm kernel oil expeller. In addition, much research has been conducted on the production of palm oil machines. To conduct any research on the development of machines to process palm oil, there has to be a good grasp of palm oil mill process. There are two types of oil palm fruits digestion machine and they are the vertical and horizontal digester. (Oglechi and Ige, 2014). A vertical digesting machine is that which fruit mesocarp are digested using a vertical shaft with beater arms at a defined orientation and distance on the shaft, whereas in a horizontal digesting machine, beater arms are used to transfer macerated fruits between the inlet and the outlet of the digestion machine (Cornet, 2001). For the machine to operate at optimum output the operating variables like speed, digesting time, temperature, load, etc have to be properly harnessed, since these will all impact on the quality and quantity of palm oil produced, and quantity of digested palm fruits including the efficiency and capacity of the machine (Nwankwojike, et al., 2011; Udo et al., 2015; Uzoma and Eseonu 2024; Aniekan et al., 2025).

Machines optimization entails enhancing their performance, efficiency and reliability using data-driven examination and adaptive turning. Real-time data collection and evaluation can be used to optimize a machine by determining areas that can be better and alter parameters or processes to achieve overall equipment effectiveness (OEE) (Offiong et al., 2025).

Asoro and Udo (2013) and Erhimona et al., (2023) focused much on optimization of their digestion machine. The motorized oil palm fruit rotary digestion machine designed and built by Asoro and Udo (2013) is a device that feeds on oil palm fruits; the machine is characterized by a feed hopper, axle, hammers, screening plate, v-belt, digestion chamber, 2hp electric motor, and frame made of standard and locally available materials. The ideal pace of the machine of digesting was established during the first experimental plan wherein ten separate samples of fresh oil palm fruit of 5kg each was fed through the hopper in order to digest following the initiation of the machine. A stopwatch was employed to record the time that the individual sample spent digesting and generating data in every one of the ten trails with varying operational speed 581-4, 591.4, 601.4, 611.4, 621.4, 631.4, 641.4, 651.4, 661.4 and 671.4rpm. It was revealed that the speed at which the digestion machine (invented by Asoiro and Udo, 2013) works best was 621.4rpm. The second experiment involved testing the performance of the digestion machine by noting how fast it digested and the efficiency at the best speed of 621.4rpm. The evaluation of the machine performance showed that it has a throughput capacity of 117.93kg/hr with performance efficiency of 64.88% operating at 621.4rpm as an optimum working speed. In some cases, Asoiro and Udo (2013) found that the rate of digestion rose with the mass of the digesting palm fruit and that the efficiency of the oil palm fruit digesting machine declined with the mass of the digesting palm fruit.

Erhimona et al., (2023) reported the optimization of locally produced palm fruit digestion machine through Response Surface Method (RSM). Response Surface Method (RSM) can be defined as a group of mathematical and statistical methods that are used to study the interaction between independent variables (factors), and a dependent variables (response). RSM is used to model and optimize processes, frequently determining optimal values of factors that maximize a desired result. RSM concepts includes; the independent variables: these are what are commonly called factors. They are the manipulatable inputs that can affect the response. Dependent Variables: this is what is commonly called response. It is what you desire to maximize or learn. Response Surface: This is a graphical display of the relationship between the factors and response commonly used to display the effects of hurdles in factors.

Modeling and Analysis: Response surface method (RSM) involves the use of techniques such as regression analysis and design of experiments to develop models to explain the relationship between factors and responses. Optimization: The goal of the response surface method is to find the optimal combination of factor levels to give the best possible response.

The design expert version 13 was used to construct an experimental design table of 28 runs. The researchers manipulated several parameters of the process including number of blades, motor speed and time of digestion

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

in a systematic manner based on the pre-established measures on the design table to achieve the best throughput and efficiency (Erhimona et al., 2023).

The objective of this work is to conduct the optimization of process variables of a newly developed vertical palm fruit digester as it affects the weight of digested and undigested fruits.

MATERIALS AND METHOD

Materials

The materials employed in this research work include the newly developed vertical palm fruit digester shown in Figure 2.1, palm fruits, computer and computer software, weighing balance, tachometer, stopwatch, thermometer, viscometer, water, containers, and burners.

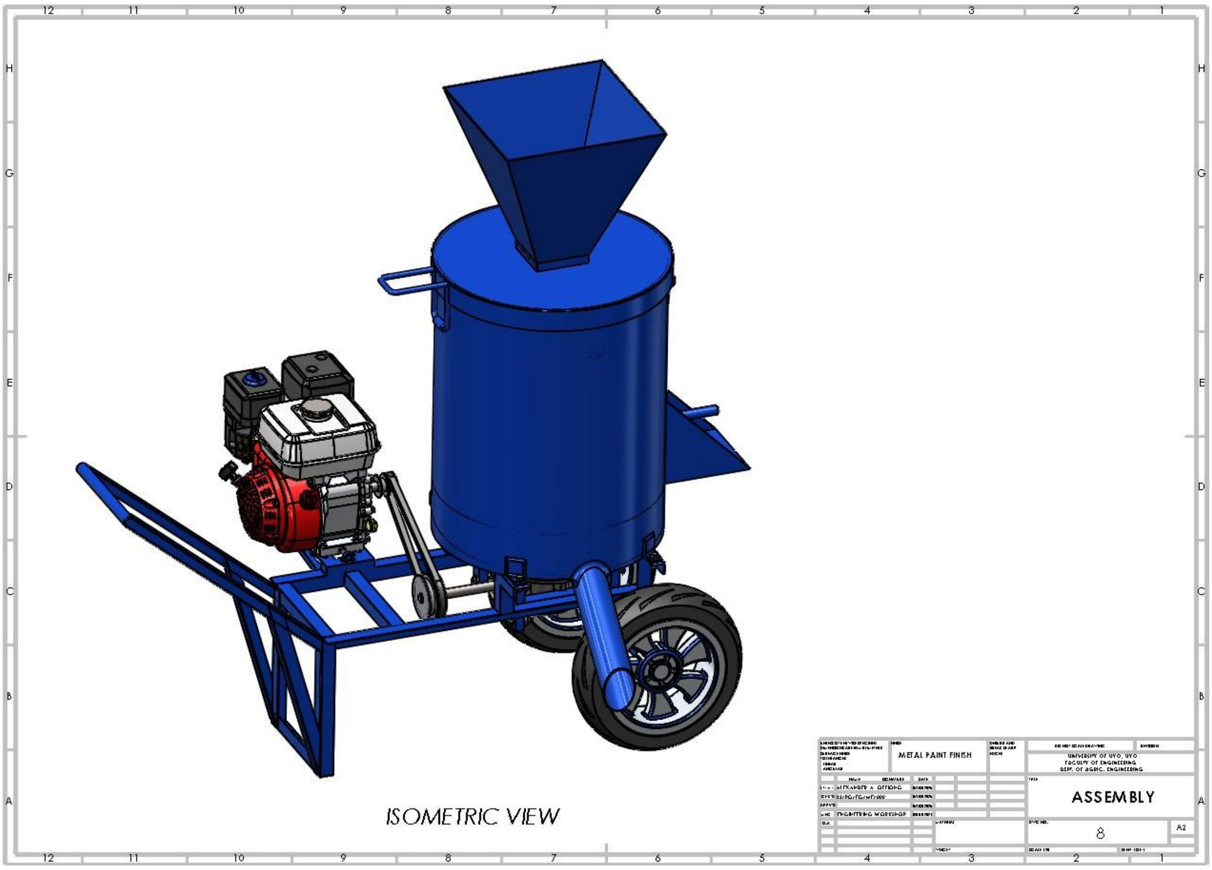


Figure 2.1: Isometric coloured drawing of the vertical palm fruit digestion machine by Reseracher (2025)

Palm Fruit Digestion Machine Functional Component Description

The key characteristics of the oil palm fruit digestion machine are: frame, hammers, stirrer shaft, digestion chamber, bevel gear, vee-belt and petrol engine.

Working Principle of the Digestion Machine

The palm fruit digestion machine is driven by the petrol engine which serves as the prime mover. The petrol engine motion is been transferred to the stirrer shaft by means of the V-belt. The bevel gear setup converts vertical motion to horizontal motion. When the hammers welded to the stirring shaft rotate they complete the digestion process. The boiled palm fruits impact with rotational hammers and walls of the digestion chambers, the fruits are pounded hence destroying the oil containing cells in the fruits. The product of the digestion of fruits is now in the form of a pulp, and the product of the digestion of the mass is in the form of a fibre/nut outlet. The process being what it is, some amount of oil is emptied out of the chamber via the oil chute on the bottom of the digestion chamber. The stirring process is in the clockwise direction. The detail information on

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

the design, Production, assembly and performance evaluation of this newly developed vertical palm fruit digester can be seen in an earlier published work by the authors Offiong, et al. 2025.

Methods

Experiment to assess the performance of the developed machine

Matured 2000kg palm fruits of tenera specie of circa was obtained at one plantation in Nsit Atai. The palm fruit was checked to determine its quality. The fruits were cleansed to extract contaminated dirt and boiled in approximately an hour at 100^0C. The experimental process assumes the same approach as Agbonkhese et al., (2018) with the difference that the test was performed using 3,4,5 and 6 arms configuration with the same speed of 580, 600, 620, 640 and 660 rpm.

Once the digester was assembled and installed with a specific arm configuration, there were experiments that were carried out with the boiled palm nuts. The fresh oil palm fruit of different weights were boiled and the boiled fruit digested through the hopper according to the time indicated in the experimental plan after which the machine was turned off. The stopwatch was used to record the digestion time taken when the digestion machine was used in the 3, 4, 5 and 6 arms hammer configuration and when running at the various speeds of 540, 580, 620 and 660 rpm. A tachometer was used to measure speed. The time in which proper maceration of the various weights of boiled fresh palm oil fruit was noted in every experiment.

The weight of palm fruits that did not digest appropriately was separated and weighted in each run. Appropriate equations as shown in Aniekan, (2025) were used to calculate the digesting or throughput capacity of the machine (kg/h) and the % efficiency.

Having identified the best setting of the digestion machine, another batch was conducted to identify this best setting Quantity and Quality of oil got during the developed machine under the use of sterilization time of 60, 90, 120, 150 and 180 minutes and under fruit storage period of 1,3,5,7 and 9 day.

At optimum setting of the digestion machine, analysis was also done to give the performance of the machine when using threaded iron rod stirring mechanism in comparison to the smooth iron rod stirring mechanism. The variables of interest above include the amount of oil and the quality of the oil since the market/industrial survey has already indicated that thread stirrer mechanism has a higher throughput and efficiency than smooth stirrer mechanism.

Parametric Analysis Design

Design Expert software version 13 was used to perform the parametric study, seeing that the software adopts the Response Surface Methodology (RSM) framework with an I-optimal custom design. This design method was chosen because it is efficient to minimize experimental experiments and to optimize the predictive performance and robustness of the models on multiple responses. The I-optimal design is also unlike the conventional factorial or central composite designs, in that it reduces the overall prediction variance and thus offers accurate parameter estimation with reduced trials.

Three independent variables were tested, which included shaft speed (A), initial weight of palm fruit (Wi, B), and number of blades (C), and six dependent responses were measured, which includes weight of digested fruit (Wd), weight of undigested fruit (Wu), time of digestion (Tn), digesting capacity (Dc), efficiency (ŋ) and the viscosity of the produced oil. These factors were systematically varied within specified ranges by the parametric design, and allowed both linear and quadratic effects, and possible interactions, to be identified. This methodology offered an organized system to investigate the functional area of the vertical palm fruit digester.

Table 2.1: Factors to be taken into consideration in this Study.

	Name	Units	Type	Levels	L[1]	L[2]	L[3]	L[4]
A [Numeric]	Speed	RPM	Discrete	4	540	580	620	660
B [Numeric]	Initial weight of palm fruit (Wi)	kg	Discrete	4	2	4	6	8
C [Categoric]	Number of Blades		Nominal	4	3	4	5	6

RESULTS AND DISCUSSION

Performance Testing of the Built Machine

Once the different parts of the palm fruit digesting machine were constructed, all the parts were combined and the machine was tested to determine how it would perform when put together with (a) three blades; (b) four blades; (c) five blades; (d) six blades. The pictorial representation of the developed palm fruit digestion machine is depicted in Figure 2.1. Figure 3.1 a-d depicts results of test runs of the developed palm fruit digestion machine. (a) fresh palm fruit before being processed by the digestion machine; (b) un-separated palm fruit after being processed by the digestion machine; (c) digested palm fruit after being processed by the digestion machine and (d) undigested palm fruit after being processed by the digestion machine.

The results of the experiment conducted to identify the performance of the developed palm fruit digestion machine at the speed of 540, 580, 620 and 680 rpm when digesting 2kg, 4kg, 6kg and 8kg in different experiment configurations are presented in Table 3.1.

(a) Sample of fresh palm fruits before **(b) Sample of unseparated palm fruits**

Being process in the digestion machine after being process in the digestion machine

(c) Sample of digested palm fruits after being process in the digestion machine

(d) Sample of undigested palm fruits after being processed in the digestion machine

Figure 3.1: a-d depicts results of test runs of the developed palm fruit digestion machine. (a) fresh palm fruit before being processed by the digestion machine; (b) un-separated palm fruit after being processed by the digestion machine; (c) digested palm fruit after being processed by the digestion machine and (d) undigested palm fruit after being processed by the digestion machine.

Parametric Analysis

To test the effect of important operation parameters on the output of the vertical palm fruit digester under the Response Surface Methodology (RSM), parametric analysis was applied to Design Expert version 13. I-optimal custom design was chosen with the aim of minimizing prediction variance and enhancing model adequacy at conserving the number of runs in the experiment. Three independent variables were considered, namely: shaft speed (A), initial weight of palm fruit (Wi, B), and number of blades (C).These were systematically promoted with approved range to objectively investigate their effects on six critical responses: in this case weight of digested fruit (Wd), and weight of undigested fruit (Wu). The software created an experimental matrix that was balanced in terms of factor combinations, allowing the study of both main effects and interaction effects. Data were fitted by statistical models, and coefficients were calculated based on coded variables to estimate the contribution of every parameter. This method made sure that linear, quadratic, and interactive effects of the factors were accurately captured. Finally, the parametric analysis provided the basis of the optimization to select noteworthy predictors and operational patterns thus giving an insight about the workings of the palm fruit digester. Table 3.1 shows the experimental results of the work.

Table 3.1: Experimental Results

	Factor 1	Factor 2	Factor 3	Response 1	Response 2
Run	A: Speed	B: Initial weight of palm fruit (Wi)	C: Number of Blades	Weight of digested fruit (Wd)	Weight of undigested fruit (Wu)
	RPM	Kg		Kg	Kg
1	620	2	4	1.76	0.24
2	660	4	5	3.7	0.3

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

3	540	4	4	3.16	0.84
4	660	2	3	1.71	0.29
5	540	8	3	6.84	1.16
6	580	8	5	6.7	1.3
7	580	2	4	1.81	0.19
8	540	6	6	5.06	0.94
9	580	8	4	6.93	1.07
10	660	4	4	3.52	0.48
11	620	4	6	3.99	0.01
12	620	6	3	5.27	0.73
13	620	6	3	5	1
14	540	6	6	5.35	0.65
15	620	4	6	3.38	0.62
16	540	2	5	1.72	0.28
17	660	8	6	6.78	1.22
18	580	2	3	1.58	0.42
19	660	6	4	5.49	0.51
20	540	2	6	1.77	0.23
21	540	4	3	3.46	0.54

Coefficients: Coded Factor.

Weight of digested fruit

The weight of digested fruit (Wd) response surface analysis showed that the model had a high significance ($F = 86.63$, $p < 0.0001$), thus indicating high predictive ability and a good fit. The weight of palm fruit at the start of the growth period (B) showed the strongest influence with a coefficient of 2.51 and very significant p-value (< 0.0001), hence, it proved to be the decisive influence of Wd. However, speed (A) and number of blades (C) yielded insignificant contribution as indicated by non-significant p-values (> 0.2). Likewise, the importance of interaction and quadratic terms (AB, AC, BC, A 2, B 2) was negligible, which highlights the linear prominence of factor B. The model residuals showed no lack of fit ($p = 0.7983$), which confirmed its reliability. The positive correlation between Wi and Wd indicates higher feed loads are associated with a predictable increment of the mass that is digested, which is physically expected of material throughput. The effect of speed and number of blades is, however, marginal, and therefore mechanical agitation and geometry have only secondary effects on the output of the digestion, at least within the ranges investigated. See Table 3.4 for confirmation of analysis also other researchers have observed that the initial weight of the palm fruit will determine the digested quantity (Nwankwojike, et al., 2011; Udo et al., 2015; Uzoma and Eseonu 2024; Aniekan et al., 2025). Table 3.2 is the coefficients as explained by coded factors of weight of digested fruit. It showed the intercept, the speed, and other factors and their combined outputs.

Table3.2: Coefficients as Explained by Coded Factors of weight of digested fruit.

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	4.41	1	0.1311	4.09	4.73	
A-Speed	0.0879	1	0.0792	-0.1058	0.2816	1.36
B-Initial weight of palm fruit (Wi)	2.51	1	0.0837	2.30	2.71	1.30
C[1]	-0.0862	1	0.0975	-0.3247	0.1523	
C[2]	0.0038	1	0.0943	-0.2268	0.2344	
C[3]	0.0072	1	0.1179	-0.2813	0.2956	
AB	-0.0534	1	0.1192	-0.3450	0.2383	1.53
AC[1]	-0.1076	1	0.1287	-0.4224	0.2072	
AC[2]	0.1002	1	0.1255	-0.2069	0.4073	
AC[3]	0.0562	1	0.1592	-0.3333	0.4456	
BC[1]	0.0672	1	0.1309	-0.2533	0.3876	
BC[2]	0.1166	1	0.1288	-0.1985	0.4316	
BC[3]	-0.1381	1	0.1657	-0.5435	0.2673	
A^2	-0.0814	1	0.1522	-0.4539	0.2911	1.59
B^2	-0.0457	1	0.1379	-0.3831	0.2918	1.33

Weight of undigested fruit

From Tables 3.3 and 3.5, the weight of undigested fruit (Wu) response analysis revealed that the model lacked statistical significance on average ($F = 3.05$, $p = 0.0888$) and thus this response exhibits less predictive power relative to others. But among the factors used, the factor weight of palm fruit (Wi) turned out to be the main determinant, with a coefficient estimate of 0.49 and a very significant effect ($p = 0.001$). This finding indicates a direct correlation between the feed load and the remaining undigested mass and is a waste in case the individual input weights do not only positively correlate with the yield of digested fruit, but also with the portions of undigested fruit expressed on a similar basis. Conversely, speed (A) and blade number (C) had minimal influences on Wu as evidenced by low F-values and non-significant p-values (> 0.24 and > 0.81, respectively). The presence of zero interaction effects (AB, AC, BC) supports again the fact that the efficiency of the digestion is less determined by the settings of the mechanical agitation at least in the operating range that is studied. The lack-of-fit is not significant ($p = 0.7983$), indicating that the model is still statistically valid with limited factor contributions (Jain and Bal, 1997; John et al., 2020; Nwankwojike et al., 2011; Offiong et al., 2025).

Table 3.3: Coefficients as a Percentage of Coded Factors of Weight of Undigested fruit.

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.5924	1	0.1311	0.2717	0.9132	
A-Speed	-0.0879	1	0.0792	-0.2816	0.1058	1.36
B-Initial weight of palm fruit (Wi)	0.4916	1	0.0837	0.2867	0.6965	1.30

C[1]	0.0862	1	0.0975	-0.1523	0.3247	
C[2]	-0.0038	1	0.0943	-0.2344	0.2268	
C[3]	-0.0072	1	0.1179	-0.2956	0.2813	
AB	0.0534	1	0.1192	-0.2383	0.3450	1.53
AC[1]	0.1076	1	0.1287	-0.2072	0.4224	
AC[2]	-0.1002	1	0.1255	-0.4073	0.2069	
AC[3]	-0.0562	1	0.1592	-0.4456	0.3333	
BC[1]	-0.0672	1	0.1309	-0.3876	0.2533	
BC[2]	-0.1166	1	0.1288	-0.4316	0.1985	
BC[3]	0.1381	1	0.1657	-0.2673	0.5435	
A^2	0.0814	1	0.1522	-0.2911	0.4539	1.59
B^2	0.0457	1	0.1379	-0.2918	0.3831	1.33

Analysis of Variance (ANOVA)

ANOVA Result of the Weight of digested fruit.

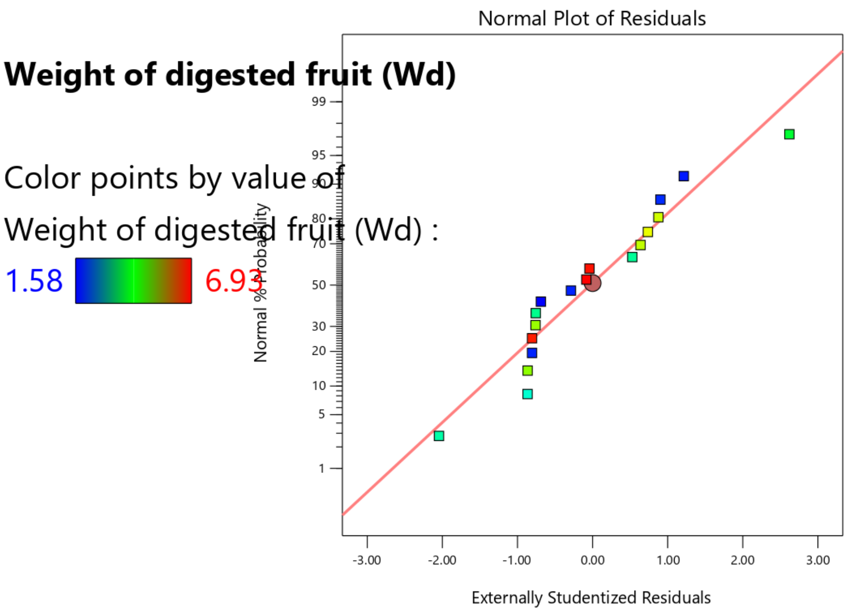
Model ANOVA of the weight of digested fruit (Wd) in Table 3.4 shows that the quadratic model is highly significant ($F=86.63$, $p<0.0001$) and that the vertical palm fruit digester can be accurately predicted within Response Surface Methodology (RSM). Without any exception, the first weight of palm fruit (B) is of paramount importance ($F=1091.33$, $p<0.0001$), identifying a positive linear interaction, wherein increasing Wi has a direct positive increase on Wd, which is intuitive as per the law of mass balance. Speed (A: $F=1.65$, $p=0.2465$) and blade count (C: $F=0.3070$, $p=0.8199$) are insignificant, indicating that there is less impact on Wd within test levels. Both the interactions (AB: $F=0.2005$, $p=0.6701$, AC: $F=0.3670$, $p=0.7798$, BC: $F=0.4797$, $p=0.7082$) and quadratic terms (A2: $F=0.2861$, $p=0.6120$, B2: $F=0.1097$, $p=0.7517$) are not significant, which suggests that the effects are additive rather than synergy. The absence of higher-order needs is an adequate fit in the model through non-significant lack of fit ($F=0.3433$, $p=0.7983$). Explained are great (adjusted R-squared = 0.984): R-sq (0.995) is outstanding (explains 99.5% of the variation) and adjusted R-sq (0.984) is fantastic (explains 98.4% of the variation). The major findings indicate that Wi is the optimization point of maximizing Wd and throughput as speed and blades can provide flexibility and do not hamper the output.

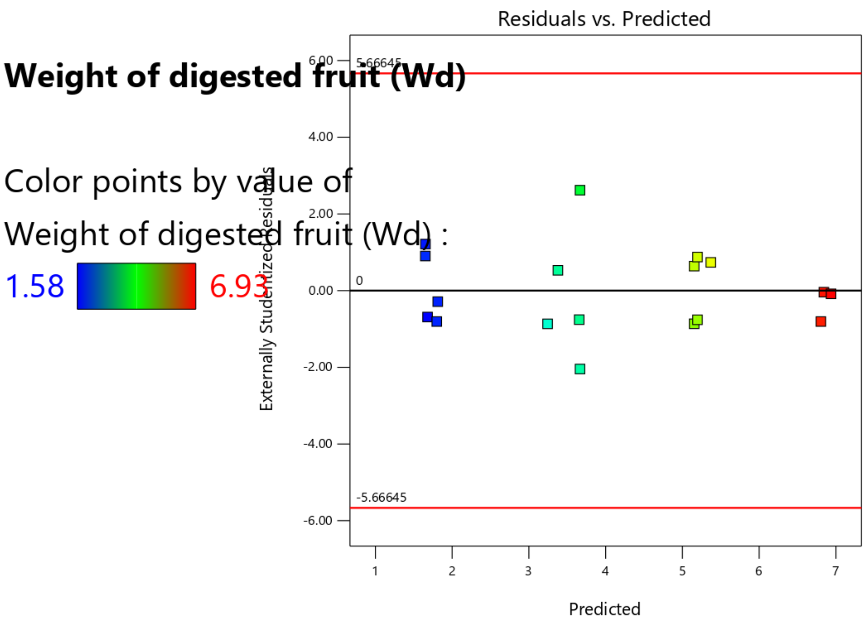
This enables scalable and effective designs of digesters towards sustainable palm oil processing to reduce undigested output. Fig.3.1 confirms that the initial weight Wi is the optimum point of maximizing Wd and throughput, as the initial weight increases so does the digested weight (Wd). The plot also indicated a proportionality between the digested weight and residual, which has been observed by several other authors (Ibrahim and Onwalu, 2005; Ibrahim et al., 2016; Ibrahim et al., 2017; Offiong et al., 2025).

Table 3.4: Analysis of Variance on the weight of digested fruit.

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	71.83	14	5.13	86.63	< 0.0001	significant
A-Speed	0.0977	1	0.0977	1.65	0.2465	
B-Initial weight of palm fruit (Wi)	64.64	1	64.64	1091.33	< 0.0001	

C-Number of Blades	0.0545	3	0.0182	0.3070	0.8199	
AB	0.0119	1	0.0119	0.2005	0.6701	
AC	0.0652	3	0.0217	0.3670	0.7798	
BC	0.0852	3	0.0284	0.4797	0.7082	
A^2	0.0169	1	0.0169	0.2861	0.6120	
B^2	0.0065	1	0.0065	0.1097	0.7517	
Residual	0.3554	6	0.0592			
Lack of Fit	0.0908	3	0.0303	0.3433	0.7983	not significant
Pure Error	0.2646	3	0.0882			
Cor Total	72.19	20				





ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

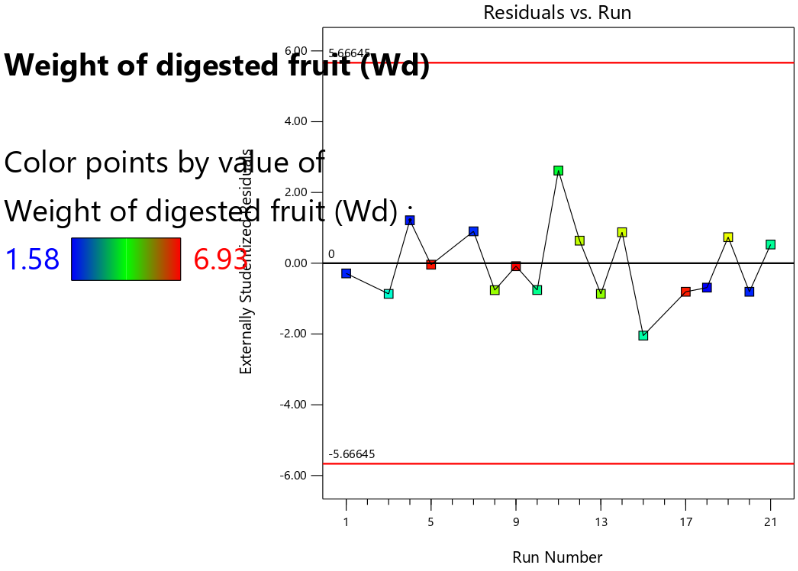


Figure 3.1: (a) Normal Probability- Residual; (b) Studentized Residuals-Predicted Response; (c) Studentized Residuals-Run (Variance Results of the weight of digested fruit)

ANOVA Result: Weight of undigested fruit

Table3.5 shows that the weight of undigested fruit (Wu) ANOVA proved that the general model was not significant ($F = 3.05$, $p = 0.0888$). The data showed a low predictive power in comparison with other responses. The only factor that was found to be significant was the initial weight of palm fruit (Wi) ($F = 35.77$, $p = 0.0010$), which concurs with the fact that the larger the input loads, the higher the undigested fraction. A, C, and all term of interaction (AB, AC, BC) were non-significant ($p > 0.24$), implying that they have only a slight effect on residual undigested mass in the investigated ranges. There was also a negligence of quadratic effects, which underscores the strength of Wi as the most important predictor. The lack-of-fit test was not significant ($p = 0.7983$), which is complemented with the residual diagnostics, in Figure 3.2, indicating that the model is adequately fit, despite its low explanatory power.

The normal probability and residual plots revealed that the point distribution was near the line which did not imply severe violations of the model assumptions. The comparatively small R^2 (0.88) in comparison with the digested fruit model however, indicates that not a lot of variance was measured by this response. The most active or influential factor on the undigested fruit weight is the initial fruit weight this is in agreement with earlier researchers (Babatunde et al., 1988; Ashraf et al., 2008; Bello et al., 2015 and Aniekan, 2025) and is also confirmed by Fig.3.2.

Table 3.5: ANOVA Results on the Weight of undigested fruit.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.53	14	0.1806	3.05	0.0888	not significant
A-Speed	0.0977	1	0.0977	1.65	0.2465	
B-Initial weight of palm fruit (Wi)	2.12	1	2.12	35.77	0.0010	
C-Number of Blades	0.0545	3	0.0182	0.3070	0.8199	
AB	0.0119	1	0.0119	0.2005	0.6701	
AC	0.0652	3	0.0217	0.3670	0.7798	

BC	0.0852	3	0.0284	0.4797	0.7082	
A^2	0.0169	1	0.0169	0.2861	0.6120	
B^2	0.0065	1	0.0065	0.1097	0.7517	
Residual	0.3554	6	0.0592			
Lack of Fit	0.0908	3	0.0303	0.3433	0.7983	not significant
Pure Error	0.2645	3	0.0882			
Cor Total	2.88	20				

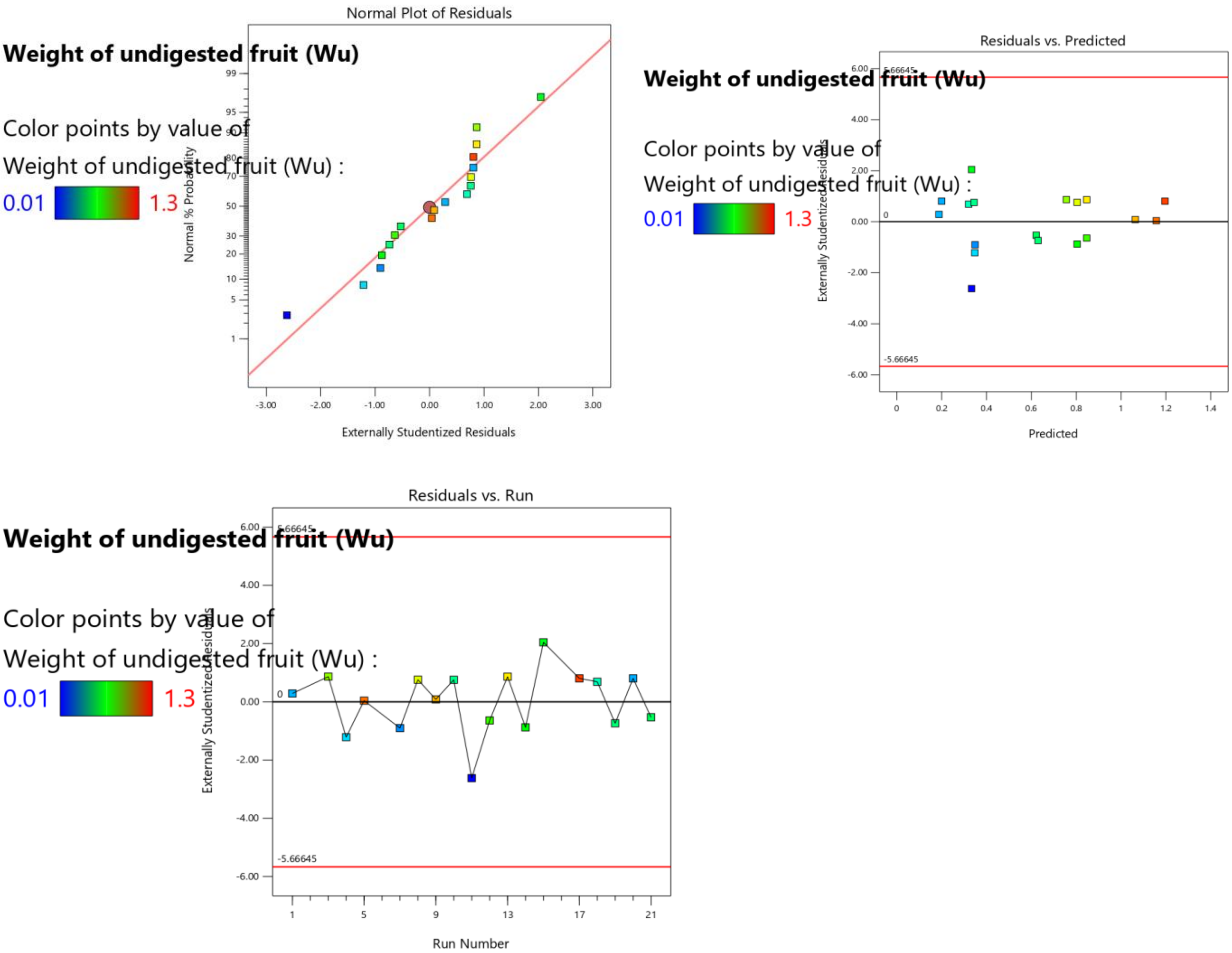


Figure 3.2: (a) Normal Probability-Residual (b); Studentized Residuals-Predicted Response (c); Studentized Residuals-Run (Variance Results of the Weight of undigested fruit)

Parameter Interactions and Contours Plots

Weight of digested fruit

Fig. 3.3 which is contour plot for the weight of digested fruit (Wd) offers a graphic display of the connection between the variables of the processes and performance in digestion. It is evident in the plot that the initial weight of palm fruit (Wi) has the most significant effect, which is the result of the ANOVA findings that only the wi (weight) of palm fruit had any significant effect ($p < 0.0001$). The weight of digested fruit increases linearly with Wi, which is a near linear correlation that validates that the weight of digested fruit rises linearly

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

with Wi. This trend can be explained by the physical principle according to which the greater the mass of feed consumed, the higher is the amount of output that is digested under the same working conditions. There was a small difference in speed (A) and blade number (C) between the contour surfaces which contributes to the non-significance of the two variables in the statistical model. The almost parallel lines of contour indicate that in the range tested, variation in velocity or blade shape does not significantly affect Wd. The effects of interaction are also of a negligible order, which can be shown by the absence of the curvature or even by the crossing contours.

Beginning with a straightforward plot of the weight of digested fruit, Figure 3.3 below demonstrates that the trend indicates the presence of multiple regression lines, which intersect at one point: This has equally been observed by several authors in their respective works (Anita et al., 2014; Asha et al., 2017; Ibiyeye et al., 2022 and Aniekan, 2025).

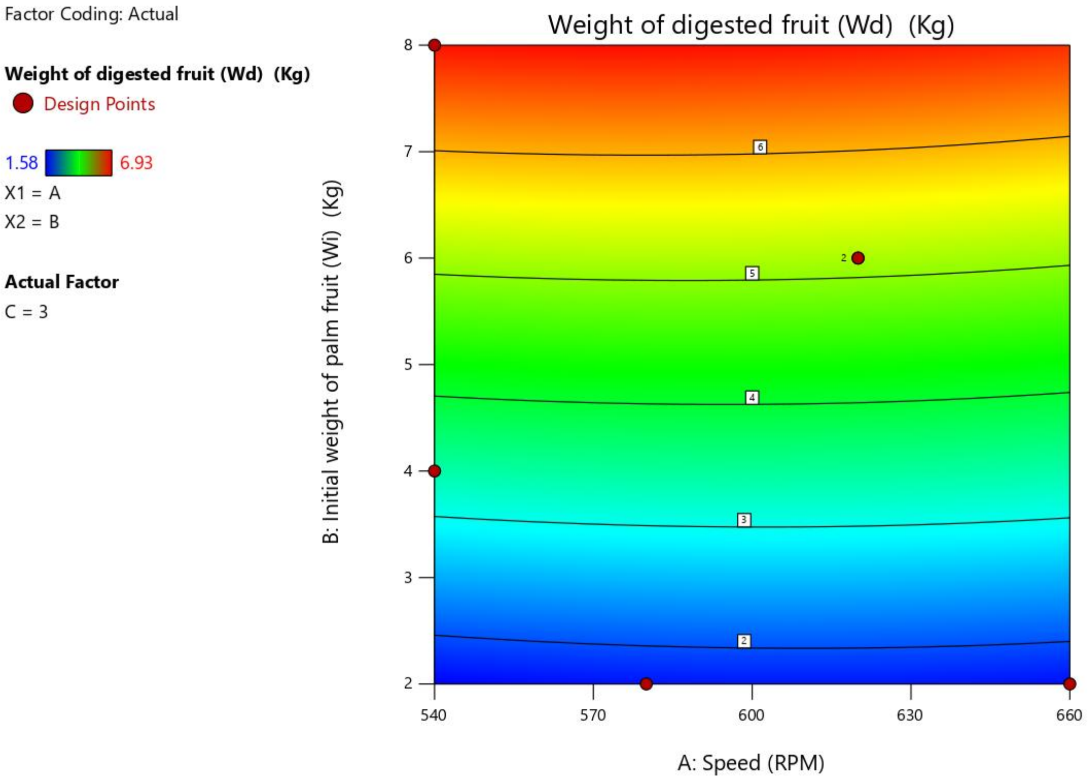


Figure 3.3: Contour Plot for the Weight of digested fruit

Weight of undigested fruit

The shape contour plot of the weight of undigested fruit (Wu) in Fig. 3.4 shows the indirect relationship between process variables and the mass remaining after digestion. The ANOVA results are validated by the visualization, indicating that the initial weight of palm fruit (Wi) is the most significant variable. When Wi is raised, the quantity of undigested residue will correspondingly increase with contour gradients illustrating the positive linear association.

This tendency suggests that, the greater the input load, the higher the digested output, but the undigested portion of the feed is similarly proportional and the necessity to use balanced feeding strategies. In contrast, adjustments in velocity (A) and the number of blades (C) lead to slight modification in the contour surface. The almost regular spacing of contours implies minimal contributions of these mechanical parameters to Wu in the experimental design. There is also no significant curvature or interaction patterns, which proves that AB, AC, and BC terms in the ANOVA model are statistically insignificant. This analysis is justified by the works of other authors like Allen et al., 2002; Amiolemhen and Eseigbe 2019; Offiong et al 2025; and Aniekan, 2025.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VII July 2026

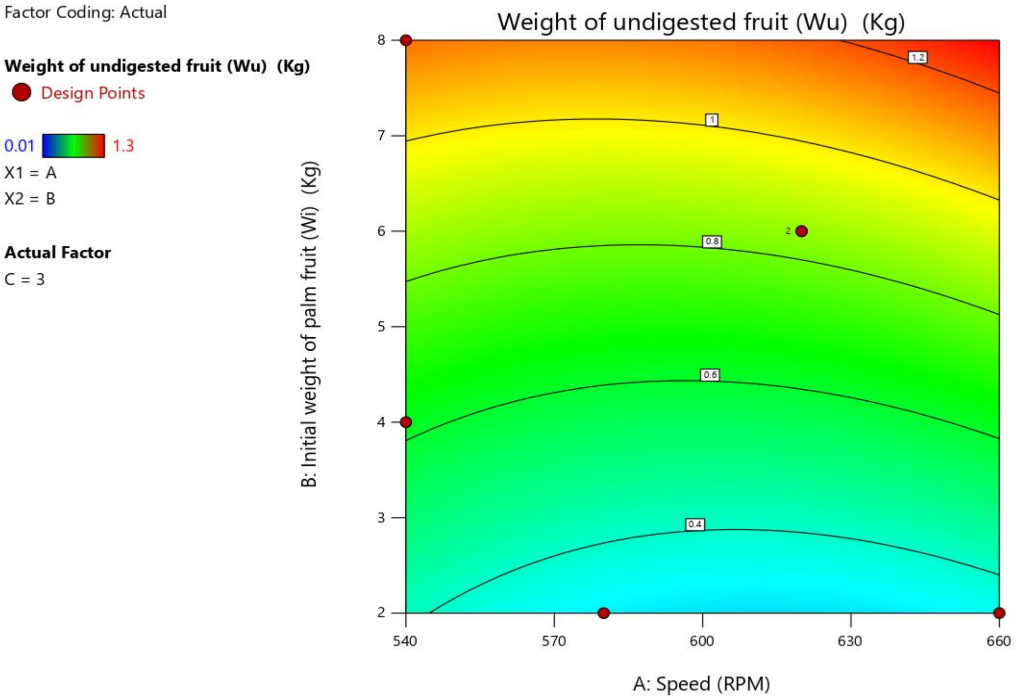
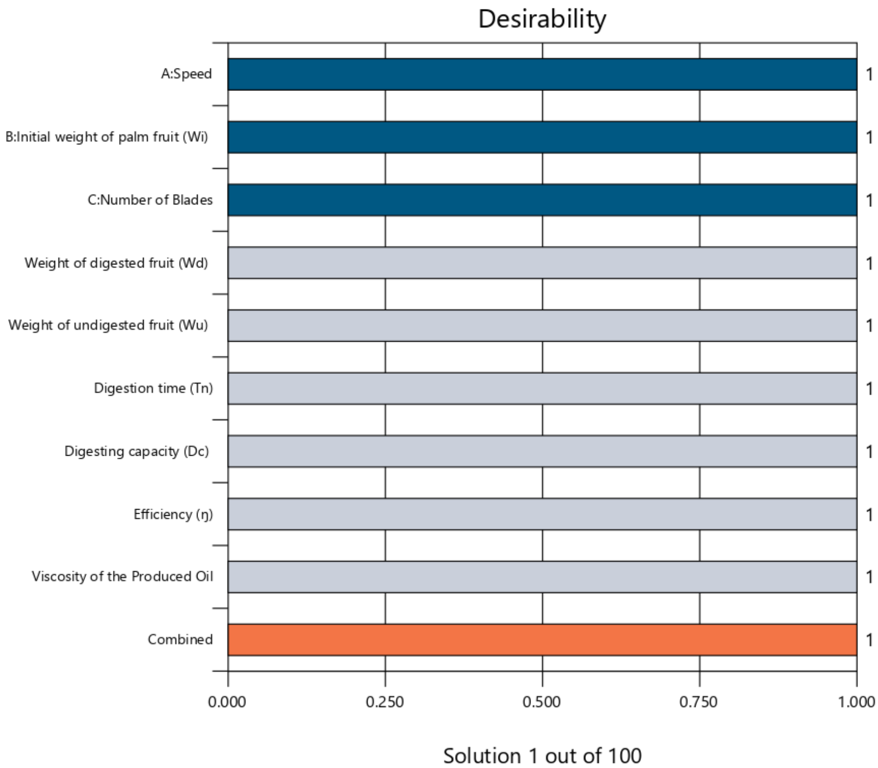


Figure 3.4: Contour Plot for the Weight of undigested fruit

Desirability Plot

Based on Response Surface Methodology (RSM), the desirability plot shown in Fig.3.5 describes the optimum operating point of the vertical palm fruit digester to achieve maximum efficiency (ŋ), digesting capacity (Dc) and minimum weight of undigested fruit (Wu), with weight of digested fruit (Wd) generated being a balanced output. The best settings, speed (A) of 595.873 RPM, starting weight (Wi, B) of 5.472 kg and using 6 blades (C)- resulting in Wd = 4.866 kg, Wu = 0.605 kg, Tn =1.095 min, Dc = 289.300 kg/h, n = 90.200 percent and viscosity = 0.048 Pa.s with a desirability of 1.000. Table 3.4 (B: F=1091.33, p=0.0001) confirms this fact with the steep contours of Wi dominating Wd and Wu (Table 3.5, B: F=35.77, p=0.0010) (Offiong et al., 2025).



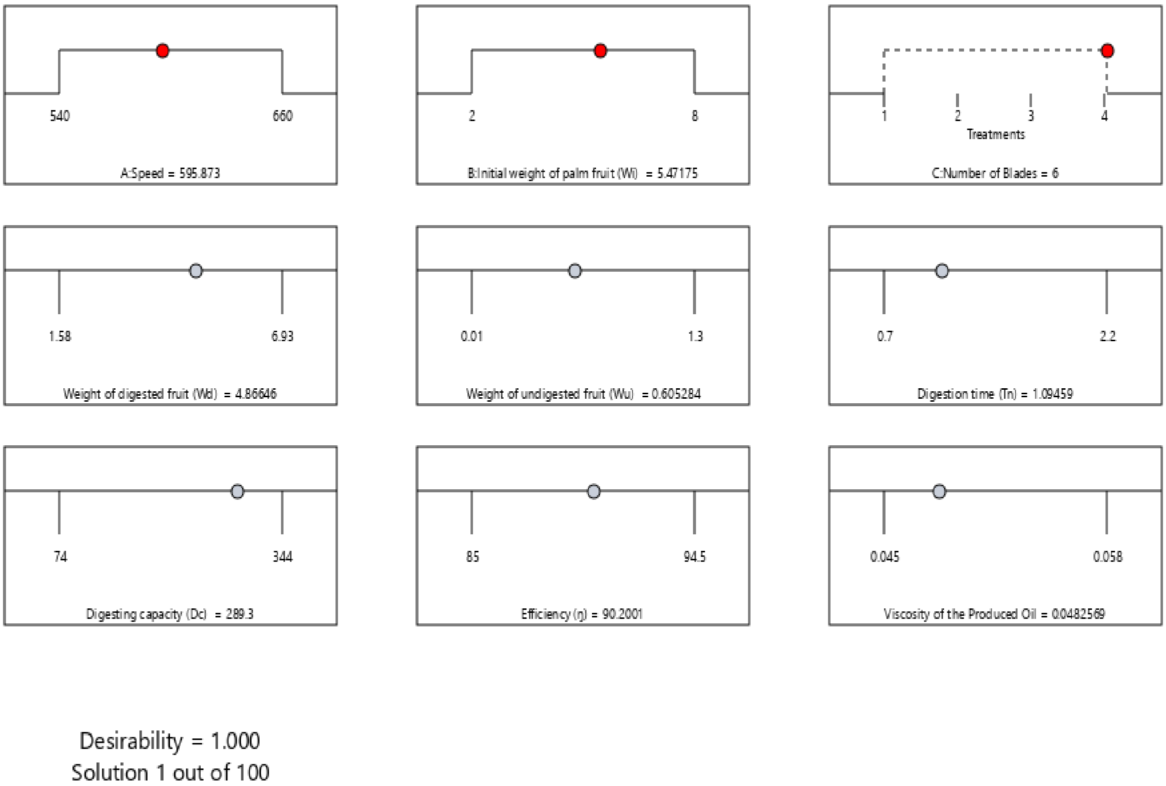


Figure 3.5: Optimisation Plot

CONCLUSION

This work has conducted a study on the 'Optimization of Process Variables of a Newly Developed Vertical Palm Fruit Digester as it Affects the Weight of Digested and Undigested Fruits', from the study the following conclusions have been drawn:

1. The optimization analysis of the palm fruit digester utilized three factors (speed, initial palm fruit weight, and number of blades) and the targeted responses are digested and undigested weight of palm fruits.

2. The weight of digested fruit (Wd) response surface analysis showed that the model had a high significance ($F = 86.63$, $p < 0.0001$), thus indicating high predictive ability and a good fit. The weight of palm fruit at the start of the growth period (B) showed the strongest influence with a coefficient of 2.51 and very significant p-value (< 0.0001), hence, it proved to be the decisive influence of Wd.

3. The weight of undigested fruit (Wu) response analysis revealed that the model lacked statistical significance on average ($F = 3.05$, $p = 0.0888$) and thus this response exhibits less predictive power relative to others. But among the factors used, the factor weight of palm fruit (Wi) turned out to be the main determinant, with a coefficient estimate of 0.49 and a very significant effect ($p = 0.001$).

4. The work showed that the quadratic model of the weight of digested palm fruit is highly significant ($F=86.63$, $p<0.0001$) and that the vertical palm fruit digester can be accurately predicted with Response Surface Methodology (RSM).

5. The weight of undigested fruit (Wu) ANOVA, proved that the general model was not significant ($F = 3.05$, $p = 0.0888$). The data showed a low predictive power in comparison with other responses. The lack-of-fit is not significant ($p = 0.7983$), indicating that the model is still statistically valid with limited factor contributions. The lack-of-fit is not significant ($p = 0.7983$), indicating that the model is still statistically valid with limited factor contributions.

6. It is evident in the plot that the initial weight of palm fruit (Wi) has the most significant effect, which agrees with the result of the ANOVA, that only the wi (initial weight of palm fruit) had any significant effect ($p < 0.0001$).

7. The ANOVA results are validated by the visualization, indicating that the initial weight of palm fruit (Wi) is the most significant variable. When Wi is raised, the quantity of undigested residue will correspondingly increase with contour gradients illustrating the positive linear association.

8. Based on Response Surface Methodology (RSM), the desirability plot describes the optimum operating point of the vertical palm fruit digester to achieve maximum efficiency (ŋ), digesting capacity (Dc) and minimum weight of undigested fruit (Wu), with weight of digested fruit (Wd) generated being a balanced output. The best settings: speed (A) of 595.873 RPM, starting weight (Wi, B) of 5.472 kg and 6 blades (C)- resulting in Wd = 4.866 kg, Wu = 0.605 kg, Tn =1.095 min, Dc = 289.300 kg/h, n = 90.200 percent and viscosity = 0.048 Pa.s with a desirability of 1.000.

REFERENCES

1. Agbonkhese, K., A., Frank, O., and Okojie, G. (2018). International Journal of Current Advanced Research ISSN: O: 2319-6475, ISSN: P: 2319-6505, Available Online at www.journalijcar.org Vol. 7; Page No. 9086-9092
2. Allen S. H., Alfred R. H., and Herman G. L., (2002) “A Textbook on the Theory and Problems of Machine Design”; Tata McGraw-Hill Publishing Company Ltd: New Delhi. pp. 113-125, pp. 205-254, pp.290-297.
3. Amiolemhen, P. E., and Eseigbe, J. A. 2019. Design and Fabrication of a Palm kernel oil expeller machine. International Journal of Engineering Trends and Technology, vol 67, Issue 6. Pp. 39-46 2010
4. Aniekan, A. (2025) Design, Production, and Optimization of Process Variables of a Vertical Palm Fruit Digester, M.Eng. Dissertation in the Department of Mechanical and Aerospace Engineering, Faculty of Engineering, University of Uyo, Uyo, Nigeria.
5. Anita, O. O; Olosunde, W., and Offiong A. (2014). Determination of optimum moisture L content of palm nut cracking for efficient production of whole kernel. Nigerian Journal of Technological Development, vol. 11, No. 2, pp. 27-30.
6. Asha, S. O., Ogenekaro, O, P., Obasha, I O., Emmanuel, S. O. and Ayewa, O. A. (2017). Development of a continues palm nuts digesting machine; science arena publications specialty. Journal of Engineering and Applied Science available online at www.sciateng.com vol. 3(4):1-19.
7. Ashraf, M., Gardner, L., & Nethercot, D. A. (2008). Structural Stainless-Steel Design: Resistance Based on Deformation Capacity. Journal of Structural Engineering, 134(3), 402–411. https://doi.org/10.1061/(asce)0733-9445(2008)134:3(402)
8. Asioro F. U. and Udo U. C. (2013). Development of Motorized Oil Palm Fruit Rotary Digester. Nigerian Journal of Technology, 32 (3), 455-462
9. Babatunde, O. O., Ige, M. T., and Makanjuola, G. A., (1988). Effect of sterilization on fruit recovery in oil palm fruit processing. Journal of Agricultural Engineering Research, vol. 41, Issue 2, pp. 75-79.
10. Bello R. S., Bello M. B., Essien B. A., Saidu M. J., (2015). Economic Potentials of Oil Palm Production and Machinery Use in UDI, Enugu State, Nigeria, Science Journal of Business and Management. Special Issue: Sustainable Entrepreneurial Developments in Agribusiness. Vol. 3, No.5-1, pp. 16- 20.
11. Cornet, R.C.(2001)). Introduction Nutritional Aspects of Palm Oil. American Journal of clinical nutrition 53: 989S – 1009S.
12. Erhimona, G.O., and Onyenanu, I.U (2023). International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181 http://www.ijert.org IJERTV12IS070009 Vol. 12 Issue 07
13. Ibiyeye, D., Dlunloyo, O., Aderemi, A., Emmanuel, I., Akala, A., and Owolola, O. (2022). Design and development of a palm kernel nut unit. Technology audit and Production Reserves, 1/3(63), pp. 30-44, doi:http://doi.org/10.15587/2706-5448.2022.253931.
14. Ibrahim A and Onwalu A.P. (2005). Technologies for Extraction of Oil from oil Bearing Agricultural Products: A Review. Journal of agricultural Engineering and Technology vol 13 pp58-89.

15. Ibrahim, 1 D., Jamıru, J., Sofuwa, O., and Onuoba, O. J., (2016). Design and performance evaluation of horizontal-shaft palm kernel cracking machine. Proceeding of Covenant University 3rd International Conference on African Development. Issues. pp. 337-3341.
16. Ibrahim, O. A., Uche, C., Mahdi, M., Michael, C. A., and Sylvester, G. (2017). Dense medium machine processing method for palm kernel/shell separation. Journal of Applied Science and Environmental Management. Vol. 21(7), pp 1336-1340. ,
17. Jain, R. K. and Bal, S. (1997). “Properties of pearl millet”, Journal of Agricultural Engineering Research, vol. 66, pp. 85–91.
18. John S., Attahiru H., and Aliyu Y. (2020). Development of a Palm kernel cracking and separator machine. International Journal of Agricultural Science and Technology, vol. 8 No. 4 pp. 47-59. www.iarcj.org, www.arsnjournals.
19. Nwankwojike B. N, Odukwe A. O. and Agunwamba J. C.(2011). “Modification of Sequence of Unit Operations in Mechanized Palm Fruit Processing”, Nigerian Journal of Technology, Vol. 30, No. 3, pp. 41-49.
20. Offiong A.A., Offiong, A., Aondona, P.T., and Ihom, A.P. (2025) Design and Production of aVertical Palm Fruit Digester, Hollex Journal of Engineering and Innovation, 13(4), 16-47.
21. Ogblechi S. R and Ige M. T. (2014). “Development of a Model to Predict the Shear Force of a Horizontal Mechanical Digester”, International Journal of Science, Technology and Society, Vol. 2, No. 6, pp. 174-178.
22. Udo, S. B., Adisa, A. F., Ismila, S. O, and Adejujyibe, S. B., (2015). Development of palm kernel nut cracking machine for rural use. Agric Eng Int: CIGR Journal 17(14): 379- 388.
23. Uzoma, S. M. and Eseonu O. (2024). Design and Fabrication Details of an improved mechanized palm fruit harvester. American Journal of Mechanical Engineering, vol. 12, No. 2, pp 19-25. Available online at http://pubs.sciepub.com/ajme/12/2/2022