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MODELING AND OPTIMIZATION OF AERODYNAMIC PROPERTIES OF PIGEON PEA (CAJANUS CAJAN (L.) MILLSP.)

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Abstract

Mathematical modeling and optimization was carried out in other to create and provide data for designing harvesting, processing, handling and storage machines or equipment using air for cleaning, sorting or separating pigeon pea seeds. Two varieties (Flavus and Bicolor) of pigeon peas seeds were conditioned from their initial moisture to 8, 10, 12, and 14% d.b, for the determination of terminal velocity and drag coefficient. Seeds samples of weight 50,100 and 150g were poured into a constructed air aerodynamic apparatus during the determination. A response surface method with an I-Optimal (IV) design was used to optimize and model both terminal and drag coefficient properties. The result obtained from the study for terminal velocity ranges from 5.2 to 11.98 m/s while that for drag coefficient ranges from 0.07 to 0.94. A reduced two factor interaction (R2FI) and reduce linear models was used for modeling data of terminal velocity and drag coefficient respectively. The two models was significant at $p<0.01$. The R2FI and Optimized values range for design consideration for harvesting machines were Moisture (13.52 - 14%), Weight (150g), Terminal velocity (11.67 - 11.98 m/s), Drag coefficient (0.18 - 0.21), Desirability (0.96 - 1.00). Those for processing and handling machines were Moisture (10 - 10.26 %), Weight (150g), Terminal velocity (7.65 0 8.2 m/s), Drag coefficient (0.42 - 0.44), Desirability (1.00). Finally those for storage structures and machines were Moisture (8%), Weight (150g), Terminal velocity (5.22 - 6.05 m/s), Drag coefficient (0.57), Desirability (1.00).

Key word: Terminal velocity, drag coefficient, modeling, optimization and design consideration.

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Introduction

Pigeon pea (*Cajanus cajan* (L.) Millsp.) among other leguminous grains belong to a sub-tribe of *Cajaninae* which in turn belong to the economically important leguminous tribe of *Phaseoleae* (Young et al. 2003 and FAOSTAT 2005). Pigeon pea could serve as an important grain for food security in sub-Sahara African (Rao et al. 2002). It is a major source of protein to about 20% of the world population and is an abundant source of minerals and vitamins (Saxena et al. 2002). Kimani, 2001 reported that global pigeon pea production had a total increase of about 54% from 1961 to 2007.

According to Gürsoy and Güzel (2010) data on physical and aerodynamic properties of agricultural products must be generated and use for design and adjustments of machines used during harvesting, separating, cleaning, handling, sorting and storing of agricultural materials and in the process of their conversion into food, feed and fodder. Other researchers who study the terminal velocity and Drag coefficient properties of agricultural seeds are listed in table 1.

Modeling is defined as a process by which ideals and concepts of Scientists and Engineers about the natural environment are presented to each other and then make changes to these ideas and concepts over time in response to new evidence and understandings. A model can also be a mathematical representation of a physical, biological or information system.

Table 1. Terminal Velocity and Drag Coefficient of Some Agricultural Materials

Agricultural Materials	**Terminal**	**Drag Coefficient**	**Source**
Paddy and head rice	5.50 – 10.50	*	*Grover and Kashyap (1980)*
Paddy husk	0.33 – 2.00	*	
Broken rice	1.10 – 8.80	*	
Groundnuts pods	6.60 – 13.20	*	
Groundnuts shell	0.33 – 3.30	*	
Pulses			*Sadynam and Grover (1983)*
Moong (Vigna radiata)	19.75 – 27.85	*	
Urd (Vigna mungo)	17.60 – 33.90	*	
Moong washed	12.65 – 25.30	*	
Urd washed	12.65 – 24.30	*	
Gram dal (Cicer arientinum)	17.60 – 27.85	*	
Lentil or Massar (Lens esculentum)	17.60 – 32.90	*	
Malka Massar (dehusked lentil)	12.65 – 30.35	*	
Masala Constituents			*Sadynam and Grover (1983)*
Black pepper (Piper nigrum)	10.90 – 32.90	*	
Dhania dried (Coriandrum)	5.50 – 13.75	*	
Jeera (Carum carui)	4.40 – 14.85	*	
Soanf (Foeniculum vulgare)	6.60 – 16.50	*	
Impurities and empty dewinged seeds of	2.8 – 3.3	*	*Sviridov (1988)*
Pine and spruce seed	3.5 – 5.5	*	
Larch	4 – 7	*	
Jojoba seeds	10		*Coates and Yazici (1990)*
Blowing	30	*	
Oil seeds (Raya, Toria, Gobi & Sarson)	5.5 – 10.45	*	*Sethi et al.(1992)*
Pumkin seeds	4.7 – 6.5	*	*Joshi et al. (1993)*
Pumkin kernels	4.27 – 5.25	*	
Amarantus seeds	3.10 - 4.25	0.6143 - 1.0245	*Kram and Szot (1999)*
Afrcan yam beans	9.9 – 18.7	$1.1x10^7 – 8.93x10^6$	*Itwange and Igbeka (2003)*
Flaxseeds	2.46 - 3.56	0.53 - 0.83	*Ayman (2009)*
Turgenia latifolia seeds	6.775 - 6.877	0.0458 - 0.0512	*Nalbandi et al. (2009)*
wheat kernels	9.587 - 9.25	0.0543 - 0.0528	
wheat	7.04 - 7.74	0.88 - 1.01	*Khoshtaghaza and*
Wheat	7.52 - 8.14	0.588 - 1.342	*Gürsoy and Güzel (2010)*
Barley	7.04 - 7.07	0.532 - 1.708	
Lentil	7.72 - 7.78	0.577 - 0.995	
Chickpea	11.15 - 12.01	0.687 - 0.915	
kernels of corn.	8.85 - 10	*	*Polyak and Csizmazia (2010)*
Chickpea	11.13	*	*Ghamari et al.(2010)*
Lentil	5.08	*	
Rice	4.92	*	
Beniseed	2.48 - 3.05	2.67 - 2.78	*layanju et al. (2008)*
Black cumin seed (Nigella sativa L.)	5.6 - 5.92	*	*Seyed et al. (2010)*
Acorn (Quercus suber L.)		*	*Mahbobeh Fos'hat et al. (2011)*
Nut	19.52	*	
Kernel	16.8	*	
Hull	4.07	*	
Soybean	7.13 - 9.24	*	*Polat et al. (2006)*
Pistachio nuts	9.8 - 12.44	*	Seyed *et al. (2007)*
Pistachio kernels	8.30 - 11.10	*	
Jatropha curcas	8.1 – 10.8	*	*Karaj and Muller(2010)*

*Not Reported

Mathematical modeling is a principled activity (Ambitious Science Teaching, 2015; Cha et al, 2000; Dym and Ivey, 1980).

Mathematical optimization can be defined as selection of best factors or elements (with regard to some set goals or constrains before the beginning of the selection) among some group of factors and element considered. More generally, optimization includes finding "best available" values of some objective function given a defined domain (or input), including a variety of different types of objective functions and different types of domains. (The Nature of Mathematical Programming, 2014; *Battiti et al 2008*

Response surface methodology (RSM) can be described as a technique that involves complex calculation for optimization process. This approach develops a suitable experimental design that integrates all of the independent variables and uses the data input from the experiment to finally come up with a set of equations that can give theoretical value of an output. The outputs are obtained from a well-designed regression analysis that is based on the controlled values of independent variables. Thereafter, the dependent variable can be predicted based on the new values of independent variables. Response surface methodology (RSM) involves the use of the following experimental designs: Central Composite Design (CCD); Box-Behnken (BB); Optimal Designs (Khairul and Mohamed 2015; Giovanni, 1983; Meilgaard et al 1991).

Optimal Designs is a flexible design structured to accommodate structured models, categorical factors and irregular (constrained) regions. Optimal Designs includes (*Stat-Ease* 2017) :

The objective of this study is to model and optimize aerodynamic properties of pigeon pea for design consideration of the pea's harvesting, separating, cleaning, handling and storing equipment that employ the use of airflow. Mechanizing the production of pigeon pea will bring great source of income to farmers in developing countries were these pea are mostly farmed.

Materials and Methods

1. *Sample collection.* The varieties (flavus and bicolor) of pigeon peas (Cajanus cajan (L.) Millsp) was sourced from Wurukum market in Benue State of Nigeria. Purchased seeds were cleaned. Varieties samples taken to the agronomy Laboratory of the University of Agriculture, Makurdi, Nigeria for identification.
2. *Seed conditioning.* A sample of 2 kg was collected from each varieties of pigeon pea. The initial moisture content, M_i, was determined using ASAE standard (ASAE, 1998). By using sampling of 2kg, calculated quantities of distilled water using equation 1(Audu et al, 2017) was added to increased their moisture condition to 8, 10, 12, and 14% d.b.

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \quad (1)$$

Where Q = mass of water to be added (kg), W_i = initial mass of the sample (kg), M_i = initial moisture content of the sample (%) d.b. and M_f = final moisture content (%) d.b.

The samples were placed in a refrigerator at a temperature ≤5 °C for 7 days. The moisture content of samples was verified before each test was conducted.

3. *Determination of Terminal Velocity and Drag Coefficient.* Terminal velocity of pigeon pea seeds was determined experimentally using an apparatus constructed by crop processing laboratory of the department of Agricultural and Environmental Engineering, University of Agriculture, Makurdi, Nigeria.

The aerodynamic properties apparatus setup is shown in figure 1. Before performing the experiments. Seeds samples of weight 50,100 and 150g were produced with four different moisture content (8,10, 12, 14% db) for both varieties. A seeds sample was placed on the wire screen inside the air column (upper chamber of the apparatus) and the fan was turned on (at the lower chamber). The speed of the fan was regulated with a switch until the seeds start to suspend in the air within the column. Then a wind vane digital anemometer was placed inside the upper chamber column of the apparatus to measure the velocity of the air. The reading on the anemometer was taken as the experimental terminal velocity of the seeds.

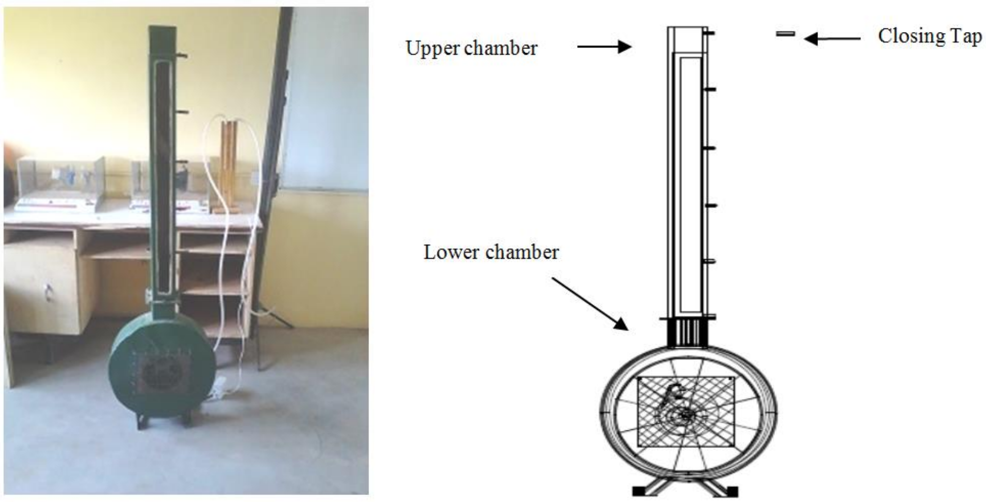


Figure 1. Constructed apparatus used for measuring Terminal velocity

The experimental drag coefficient was calculated using Equation 2 (Hauhouot-O'Hara et al., 2000), which contains physical properties data which was obtained for the purpose of this research work. The length of the seeds ranges from 9.9mm to 8.09mm with a mean value of 8.71mm, the breath axes the dimension ranges from 7.03mm to 5.23mm with a mean value of 6.28mm, the bulk density is 5.53g/mm^3, the projected area varied from 38.83mm^2 to 36.49mm^2, the weight of pigeon pea seed ranges from 4.63g to 4.28g.The air or fluid density is assumed to be 1.15kgm^{-3} at constant laboratory temperature, and mass density of 50, 100 and 150g respectively:

$$C_d = \frac{2W(\rho_p - \rho_f)}{V_t^2 A_p \rho_p \rho_f} \qquad (2)$$

Where C_d = Drag coefficient of the samples, W = weight of samples (kg), V_t = terminal velocity (m/s), ρ_f = fluid density (kgm^{-3}), A_p = projected Area (m^2), ρ_p= mass density (kgm^{-3})

4. *Statistic Analysis.* All optimizations and modeling were done using Design Expect Software (version 10) produced by State Ease company. For both terminal and drag coefficient properties, a response surface method with an I-Optimal (IV) design was used to optimize and model them.

Result and Discussion

The result obtained from the study for terminal velocity ranges from 5.2 to 11.98 m/s while that for drag coefficient ranges from 0.07 to 0.94 (Table 2 and 3). Similar ranges were obtained by other researchers for agricultural seeds as shown in table 1. The mean terminal velocity was 8.26 m/s with a standard deviation of 1.97, while the mean for drag coefficient was 0.54 with a standard deviation of 0.29.

A reduced two factor interaction (R2FI) model (Equation 3) was used for modeling data of terminal velocity. This choice was because among all models considered the R2FI model had the highest predicted R-square and high lack of fit p-value (see Table 4). Table 5 shows the Analysis of variance (ANOVA) for Response Surface Reduced 2FI Model of terminal velocity data. It shows that the R2FI model was significant ($P<0.01$) with F-value of 56.72. This significant in the model implies that there is only a 0.01% chance that an F-value this large could occur due to noise. All three main effects in the model, moisture, weight and variety were found to be significant (F values greater than 0.1 are not significant) to the model. These significant occur because moisture increase the sizes of the seeds given it more weight while weight offer more resistance to lift force.

Table 2. Experimental Results of Terminal Velocity and Drag Coefficient

Run	***Factors***			***Responses***	
	Moisture	**Weight**	**Variety**	**Terminal Velocity**	**Drag Coefficient**
	%	**g**		**m/s**	
1	14	100	Flavus	10.84	0.2
2	8	100	Flavus	5.61	0.93
3	14	50	Flavus	9.26	0.42
4	8	100	Flavus	5.8	0.93
5	10	150	Flavus	8.38	0.17
6	10	50	Flavus	7.3	0.68
7	14	150	Flavus	11.98	0.84
8	10	100	Bicolor	7.2	0.45
9	10	100	Bicolor	7.6	0.7
10	14	100	Bicolor	11	0.19
11	10	150	Flavus	8.9	0.18
12	10	100	Flavus	7.33	0.43
13	8	150	Bicolor	5.2	0.47
14	10	100	Bicolor	7.5	0.75
15	12	50	Flavus	7.22	0.71
16	14	50	Bicolor	8.9	0.46
17	10	100	Bicolor	7.7	0.72
18	8	50	Bicolor	7.5	0.94
19	14	150	Bicolor	11.64	0.07

Table 3. Model design Summary for terminal velocity and Drag Coefficient

Factors Characteristics Before and After Analysis									
Names	**Units**	**Type**	**Subtype**	**Minimum**	**Maximum**	**Coded Values**		**Mean**	**Std. Dev.**
Moisture	%	Numeric	Discrete	8	14	-1.0=8	1.0=14	10.94	2.34
Weight	g	Numeric	Discrete	50	150	-1.0=50	1.0=150	100	37.27
Variety		Categorical	Nominal	Flavus	Bicolor			/	

Responses Characteristics Before and After Analysis										
Names	**Units**	**Obs**	**Analysis**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**	**Ratio**	**Trans**	**Model**
Terminal Velocity	m/s	19	Polynomial	5.2	11.98	8.25	1.96	2.3038	None	R2FI
Drag Coefficient		19	Polynomial	0.07	0.94	0.53	0.28	13.4286	None	R Linear

Software Setting for Analysis: *File Version* –10.0.1.0; *Study Type* – Response Surface; *Design Type* **–** I-optimal; *Design Model* – Quadratic; *Subtype* – Randomized; *Runs* **–** 19; *Blocks* – No Blocks.

In this study only the interaction between moisture vs. weight and weight vs. variety has significant ($p<0.05$) on terminal velocity. This also occurs because when seeds absorb more moisture their weight increases because of high turbidity in the cell structure. Also certain variety comes with the ability to retain moisture which increases seeds weight. This increases in weights offer resistance to lifting force of the air. The R2FI model had an R-Squared of 0.9562, which shows the model high ability to predict. The different between the Adj R-Squared of 0.9393 and Pred R-Squared of 0.8589 shows the accuracy of prediction of the model and this difference should not be greater than 0.2 (Stat-Ease, 2017). For the R2FI model, the difference between Adj R-Squared and Pred R-Squared is less than 0.2 which makes it an accurate predicting model.

Table 4. Models Analysis for Terminal Velocity

	Sequential	**Lack of Fit**	**Adjusted**	**Predicted**	
Source	**p-value**	**p-value**	**R-Squared**	**R-Squared**	
Linear	< 0.0001	0.0022	0.8004	0.6785	
2FI	0.0007	0.0289	0.9371	0.8210	Suggested
Quadratic	0.8935	0.0164	0.9262	0.6663	
Cubic	0.0164		0.9848		Aliased

Table 5. ANOVA for Response Surface Reduced 2FI Model for Terminal Velocity

	Sum of		**Mean**	**F**	**p-value**	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	66.54	5	13.31	56.72	< 0.0001	significant
A-Moisture	*54.95*	*1*	*54.95*	*234.21*	*< 0.0001*	
B-Weight	*2.61*	*1*	*2.61*	*11.13*	*0.0054*	
C-Variety	*1.019E-004*	*1*	*1.019E-004*	*4.342E-004*	*0.9837*	
AB	*5.87*	*1*	*5.87*	*25.00*	*0.0002*	
BC	*1.64*	*1*	*1.64*	*6.97*	*0.0204*	
Residual	3.05	13	0.23			
Lack of Fit	*2.76*	*8*	*0.34*	*5.88*	*0.0335*	*significant*
Pure Error	*0.29*	*5*	*0.059*			
Cor Total	69.59	18				

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. R2FI model ratio of 26.744 indicates an adequate signal. This signal shows that this model can be used to navigate the design space. A press of 9.82 shows how the model fits each point in the design. A -2 Log Likelihood of 19.16 shows the likelihood that the fitted model is the correct model. A BIC of 36.83 shows a penalized likelihood statistic used to choose the best model for a large design, while AICc of 38.16 shows a penalized likelihood statistic used to choose the best model for a small - medium design (Table 6). The Diagnostics Analyses graphs for Response Surface Reduced 2FI Model for Terminal Velocity are shown in figure 2. Both the predicted vs. actual graph and the normal plot of residual graph shows model points close to the diagonal line, which indicate that the R2FI model had a good level of prediction. A 3D Surface graphs for Response Surface Reduced 2FI Model for Terminal Velocity for both varieties were displayed in figure 3. These 3D graphs indicate highest point of achieving terminal velocity by combining both factors. The models (R2FI & RLinear) equations are:

Flavus

$T_v = 5.39865 + 0.0944614\,M - 0.0530036\,W + 0.00653636\,x\,10^{-3}\,MW$ ………………. *(3)*

Bicolor
$T_v = 7.07293 + 0.0944614\, M - 0.0697\, W + 0.00653636\, x\, 10^{-3}\, MW$ ………………. *(4)*

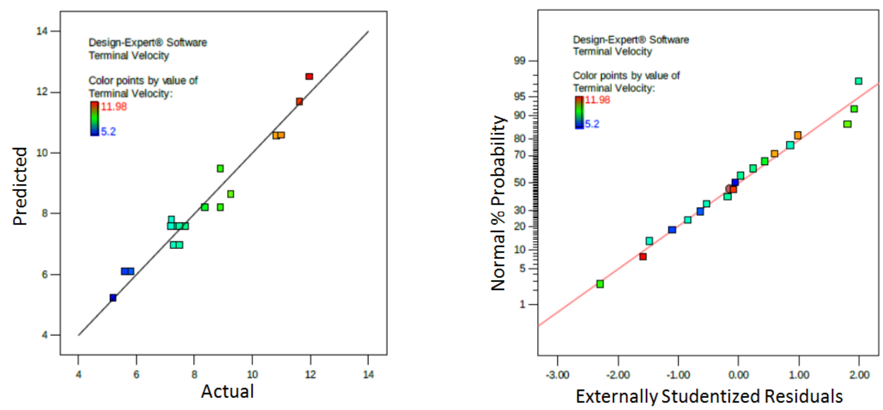
Flavus/ Bicolor
$C_D = 1.57154 - 0.0649135\, M - 0.00321965\, x\, 10^{-3}\, W$ ………………… *(5)*

Where, Tv = terminal velocity (m/s), C_D = Drag Coefficient, M = moisture (%), W = weight (g).

Table 6. Statistic description for Response Surface Reduced 2FI Model for Terminal Velocity

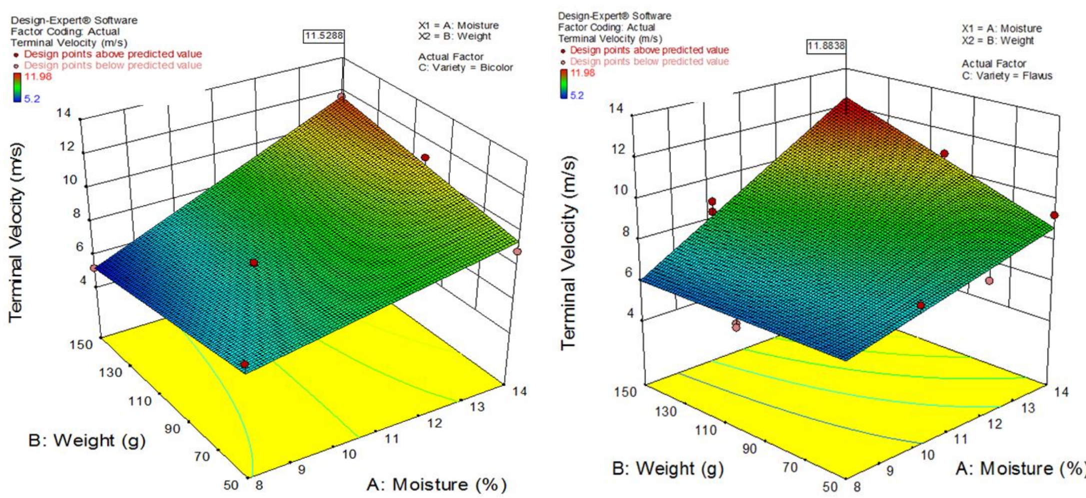
Parameter	Value
Std. Dev.	0.48
Mean	8.26
C.V. %	5.87
PRESS	9.82
-2 Log Likelihood	19.16
R-Squared	0.9562
Adj R-Squared	0.9393
Pred R-Squared	0.8589
Adeq Precision	26.744
BIC	36.83
AICc	38.16

A reduced linear model (Equation 7) was used for modeling data of drag coefficient. This choice was because among all models considered the Reduced linear model had the highest predicted R-square and high lack of fit p-value (see Table 7). Table 8 shows the Analysis of variance (ANOVA) for Response Surface Reduced linear Model of drag coefficient data. It shows that the Reduced linear model was significant (P<0.01) with F-value of 0.0112. This significant in the model implies that there is only a 0.01% chance that an F-value this large could occur due to noise. Among the three main effects in the model, two main effects moisture and weight were found to be significant (F values greater than 0.1 are not significant) to the model, while one main effect variety was found not to have any significant (p<0.05) on the model. This occur because moisture increase the sizes of the seeds given it more weight while weight offer more resistance to lift force. For drag coefficient no interactions were found to be significant (p<0.05) to the model. This is because the drag force is mostly influence by the fluid of the medium. Similar observation has been reported by: Kram and Szot (1999); Itwange and Igbeka (2003); Ayman (2009); Nalbandi et al. (2009); Gürsoy and Güzel (2010) .The Reduced linear model had an R-Squared of 0.4297. The different between the Adj R-Squared of 0.3584 and Pred R-Squared of 0.0874 shows the accuracy of prediction of the model and this difference should not be greater than 0.2 (*Stat-Ease* 2017). For the Reduced linear model, the difference between Adj R-Squared and Pred R-Squared is less than 0.2 which makes it an accurate predicting model, although it had a low R-Square. "Adeq Precision" ratio of 7.805 indicates an adequate signal. This signal shows that this model can be used to navigate the design space. A press of 1.35 shows how the model fits each point in the design. A -2 Log Likelihood of -5.29 shows the likelihood that the fitted model is the correct model. A BIC of 3.54 shows a penalized likelihood statistic used to choose the best model for a large design, while AICc of 2.31 shows a penalized likelihood statistic used to choose the best model for a small - medium design (Table 9). The diagnostics analyses graphs for response surface reduced linear model for drag coefficient are shown in figure 4. Both the predicted vs. actual graph and the normal plot of residual graph shows model points close to the diagonal line, which indicate that the reduced linear model had a good level of prediction. A 3D Surface graphs for response surface reduced linear model for drag coefficient for both varieties were displayed in figure 5. These 3D graphs indicate highest point of achieving drag coefficient by combining both factors.



a) b)

Figure 2. Diagnostic Analyses graphs for Response: a) predicted vs. actual; b) normal plot of residuals



a) b)

Figure 3. 3D Surface graph for Response Surface Reduced 2FI Model for Terminal Velocity**:** a) Flavus; b) Bicolor

Table 7. Models Analysis for Terminal Velocity

Source	Sequential p-value	Lack of Fit p-value	Adjusted R-Squared	Predicted R-Squared	
Linear	0.0327	0.0236	0.3187	-0.0193	Suggested
2FI	0.3515	0.0218	0.3449	-0.8366	
Quadratic	0.5881	0.0150	0.2931	-2.4920	
Cubic	0.0150		0.8601		Aliased

Post analysis for the models was performed. Both terminal velocity and drag coefficient models were confirmed. The confirmation is shown in table 10. For terminal velocity, the predicted mean value of 8.33m/s lies between the 95% predicted interval (95% PI) lowest Value of 7.23m/s and that for the 95% predicted interval (95% PI) highest value of 9.43m/s. Also for drag coefficient, the predicted mean value of 0.54 lies between the 95% predicted interval (95% PI) lowest Value of 0.037 and that for the 95% predicted interval (95% PI) highest value of 1.03.

Table 8. ANOVA for Response Surface Reduced Linear Model for Drag Coefficient

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.63	2	0.32	6.03	0.0112	significant
A-Moisture	*0.42*	*1*	*0.42*	*7.89*	*0.0126*	
B-Weight	*0.26*	*1*	*0.26*	*4.91*	*0.0416*	
Residual	0.84	16	0.053			
Lack of Fit	*0.78*	*11*	*0.071*	*6.22*	*0.0281*	*significant*
Pure Error	*0.057*	*5*	*0.011*			
Cor Total	1.48	18				

Table 9. Statistic description for Response Surface Reduced Linear Model for Terminal Velocity

Parameter	Value		Value
Std. Dev.	0.23	R-Squared	0.4297
Mean	0.54	Adj R-Squared	0.3584
C.V. %	42.56	Pred R-Squared	0.0874
PRESS	1.35	Adeq Precision	7.805
-2 Log Likelihood	-5.29	BIC	3.54
		AICc	2.31

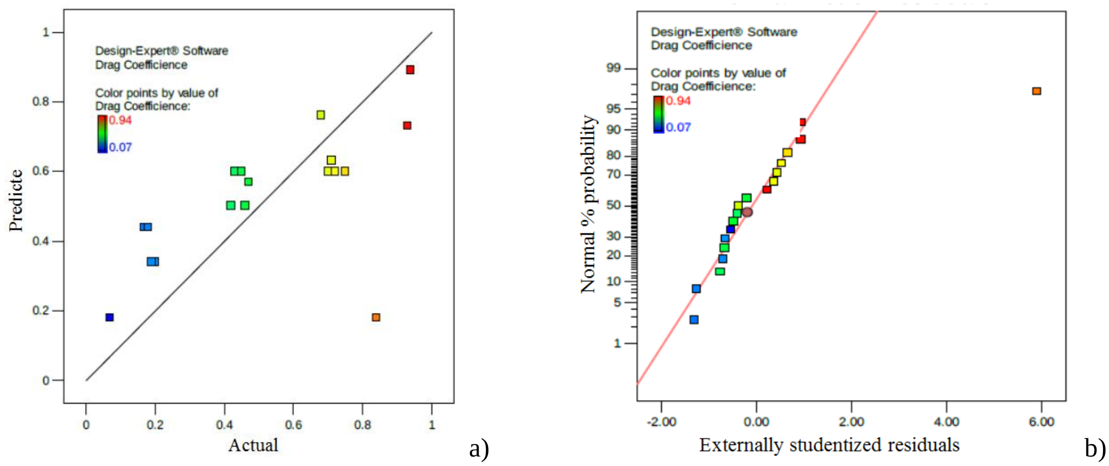


Figure 4. Diagnostic Analyses graphs for Response Surface Reduced Linear Model for Drag Coefficient: a) predicted vs. actual; b) normal plot of residuals.

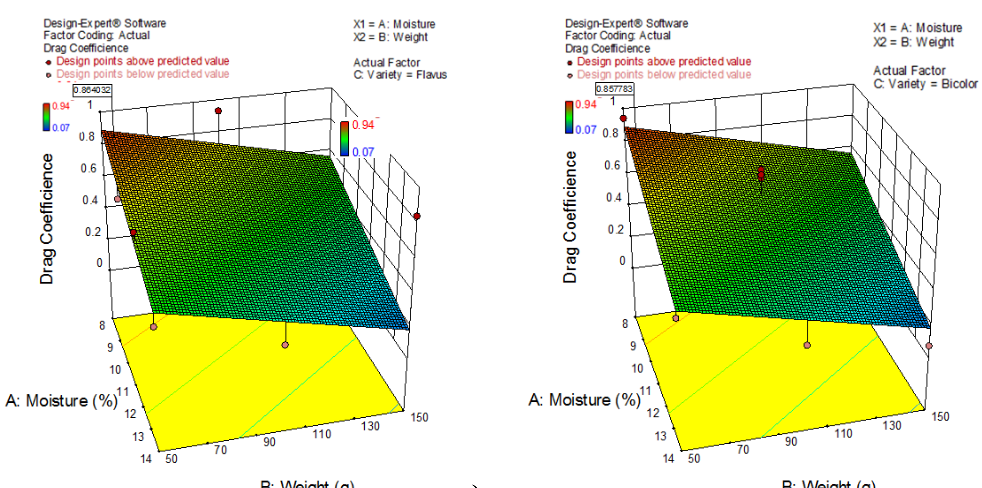


Figure 5. 3D Surface graph for Response Surface Reduced Linear Model for Drag Coefficient: a) Flavus; b) Bicolor

Table 10. Confirmation Report Table for Terminal Velocity and Drag Coefficient Models

Two-sided			Confidence = 95%	n =1					
Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding	Factor		
A	Moisture	11.00	8.00	14.00	0.00	Actual	A		
B	Weight	100.00	50.00	150.00	0.00	Actual	B		
C	Variety	Flavus	Flavus	Bicolor	N/A	Actual	C		
Response	**Predicted Mean**	**Predicted Median**[1]	**Observed**	**Std Dev**	**n**	**SE Pred**	**95% PI low**	**Data Mean**	**95% PI high**
Terminal Velocity	8.32736	8.32736	-	0.484	1	0.51	7.23	8.33 **(Confirmed)**	9.43
Drag Coefficient	0.535531	0.535531	-	0.229	1	0.24	0.037	0.54 (**Confirmed**)	1.03

[1] For transformed responses the predicted mean and median may differ on the original scale. See help for details.

Optimization of aerodynamic properties (terminal and drag coefficient) were carried out for design consideration of machines for harvesting: processing and handling: storage structures and machines of pigeon pea seeds using air for cleaning and separation. Results obtained were:

1. Optimization For design consideration of harvesting machines using air to separate and clean pigeon pea seeds. The best combination of factors and responses with the highest desirability are:
   a. Variety (Bicolor), Moisture (14%), Weight (150g), Terminal velocity (11.67m/s), Drag coefficient (0.18), Desirability (1.00).
   b. Variety (Flavus), Moisture (13.52%), Weight (150g), Terminal velocity (11.98m/s), Drag coefficient (0.21), Desirability (0.96).

2. Optimization For design consideration of harvesting machines using air to separate and clean pigeon pea seeds. The best combination of factors and responses with the highest desirability are:
   a. Variety (Bicolor), Moisture (14%), Weight (150g), Terminal velocity (11.67m/s), Drag coefficient (0.18), Desirability (1.00).
   b. Variety (Flavus), Moisture (13.52%), Weight (150g), Terminal velocity (11.98m/s), Drag coefficient (0.21), Desirability (0.96).

3. Optimization For design consideration of processing and handling machines using air to separate and clean pigeon pea seeds. The best combination of factors and responses with the highest desirability are:
   a. Variety (Flavus), Moisture (10%), Weight (150g), Terminal velocity (8.2m/s), Drag coefficient (0.44), Desirability (1.00).
   b. Variety (Bicolor), Moisture (10.26%), Weight (150g), Terminal velocity (7.65m/s), Drag coefficient (0.42), Desirability (1.00).

4. Optimization For design consideration of storage structures and machines using air to separate and clean pigeon pea seeds. The best combination of factors and responses with the highest desirability are:
   a. Variety (Bicolor), Moisture (8%), Weight (150g), Terminal velocity (5.22 m/s), Drag coefficient (0.57) , Desirability (1.00).
   b. Variety (Flavus), Moisture (8%), Weight (150g), Terminal velocity (6.05 m/s), Drag coefficient (0.57), Desirability (1.00).

Optimized result for terminal velocity and drag coefficient of pigeon pea for harvesting machine are higher (11.67 - 11.98m/s) than any other machines design consider in this study. This is because harvest machines deal with high moisture seeds which will require high velocity air to suspend them for cleaning and separating from other materials. This high upward force of the air will cause the drag coefficients to be reduced (0.18-0.21) (i.e. upward force of the air trying to cancel out the downward force of the seeds). This results means that the power requirement for harvesting machine in using air to clean and separate pigeon pea is higher (due to its terminal velocity) than in other machines design considered in this study. The 3-D desirability graph in figure 6 (a) shows that in designing harvest machines for pigeon pea both moisture and weight of seeds need to be at their highest values to achieve optimal results.

For the designing of processing and handling machines the terminal velocity that would be considered as shown in this study is lower (8.2 - 7.65 m/s) than that of the harvesting machines. This can be attributed to the fact that processing and handling operations are mostly carried out on seeds with lower moisture level than that during harvest. Also the drag coefficient is higher (0.44 - 0.42) this signify that lower power is require to attain terminal velocity than that of the harvest design. The 3-D desirability graph in figure 6 (b) shows that in designing processing and handling machines for pigeon pea optimal desirability is achieved at moisture range of 10 – 12% and at maximum weight of seeds range.

Optimal design consideration values for storage structures and machines using air to separate and clean pigeon pea seeds for terminal velocity are lower (6.05 - 5.22m/s) than those obtain from harvest, processing and handling machines. This means that lower power requirement is needed to achieve cleaning or separating of pigeon pea here than any other machine considered in this study. Their drag coefficients are also higher (0.57) than any of the machines considered in the study as well. The 3-D desirability graph in figure 6 (c) shows that in designing storage structures and machines for pigeon pea the optimal desired values occur when moisture is at 9% and weight of seeds are at maximum range.

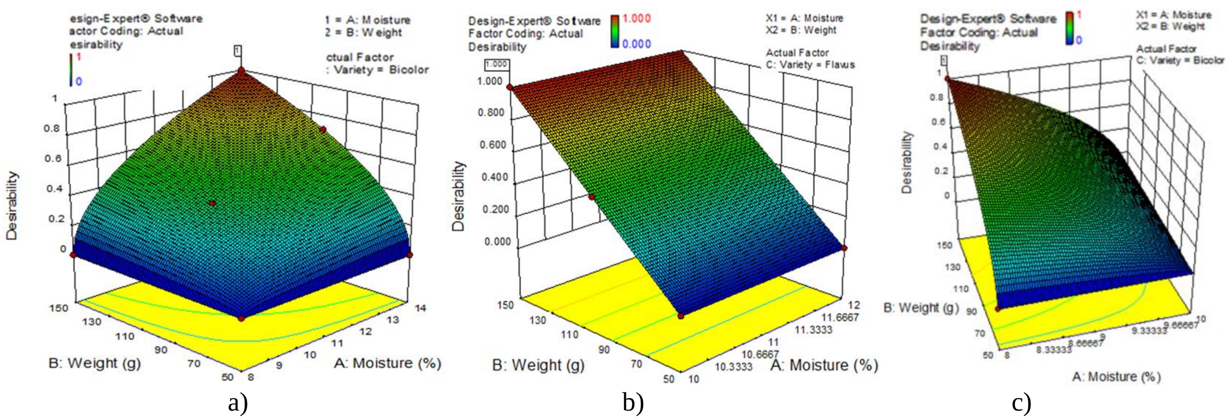


Figure 6. 3D optimization desirability graphs for designing Cleaning and separating equipments for agricultural purposes: a) Harvesting machines; b) Processing and handling machines; c) Storage structures and machines.

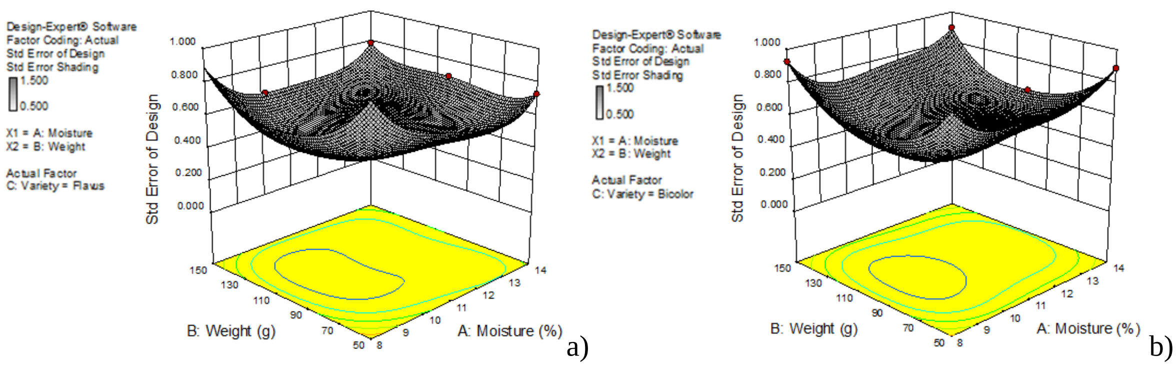


Figure 7. 3D graph for the standard error of the models generated for the pigeon pea varieties: a) Flavus; b) Bicolor

The Standard errors of the designed models for optimizing the terminal velocity and drag coefficients are shown in figure 7 for the two varieties of pigeon pea considered. The graph shows that minimum error occurs at the middle values of moisture and weight for both varieties. This is because at these values there is even distribution of both moisture and weight across a single seed of pigeon pea.

Conclusion

Conclusions drawn in this study are as follows:

1. Among all predictive models considered a reduced two factor interaction (2FI) model was the best for modeling terminal velocity while reduce linear model was the best for drag coefficient.
2. Pigeon pea seeds had higher terminal velocity and lower drag coefficient during harvest and lower terminal velocity and higher drag coefficient during storage.
3. Among the three machines design optimization considered in this study, harvest machines require more power to overcome or attain the terminal velocity of pigeon pea, while storage structures and machine require lower power when using air for cleaning and separating.

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