MODELING THE AIR FLOW RESISTANCE OF BULK SPONGE GOURD (*LUFFA CYLINDRICA*) SEEDS

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ABSTRACT

The knowledge of airflow resistant of agricultural materials is important to the design of drying and aeration systems and enhances proper fan selection for these systems. This study investigated the pressure drop across a bed of sponge gourd (Luffa cylindrica) seeds at moisture contents in the range of 9.98 to 16.5% (w.b), airflow rate of 0.11 to 0.32 $m^3s^{-1}m^{-2}$, material bed depth (0.2 to 0.8 m) and bulk density (loose, medium, and high). Pressure drop data was fitted to three common airflow resistance models (Shedd's, Hukill and Ives's, and Ergun's models). An empirical equation comprised bulk density, moisture content, and airflow rate was also developed to predict the pressure drop of sponge gourd seeds. Results obtained indicated that the airflow resistance of sponge gourd seeds increased with increase in airflow rate, bed depth but decreased with moisture content. Increased bulk density resulting from loose to densely filled resulted in an increase in resistance to airflow. Shedd model was selected to be the best for predicting pressure drop across bulk sponge gourd seeds for all the condition studied due to its high value for Coefficient of Determination (R^2) of 0.996 and a low root mean square error value (0.0279) compared to other models. The empirical equation developed predicted well the pressure drop with R^2 and RMSE values of 0.950 and 0.264 respectively.

INTRODUCTION

The property of any biomaterial depends on the level of moisture in them. Since the moisture content of the harvested seed crops is always considerably higher than the moisture required for processing or for safe storage, reducing the temperature and moisture content or humidity around the agricultural products during storage is necessary to avoid microbial and insect growth. This moisture can usually be reduced by forcing air with the proper temperature and relative humidity through the product by using forced heated or unheated air (fans), or natural drying. Drying is the first step in reducing quantitative and qualitative losses of grain after harvest. A combination of temperature and moisture control is optimal in minimizing deterioration during the storage. When air is forced through a porous bed of materials like agricultural products, it must travel through narrow paths between individual particles. Friction along air paths creates resistance to airflow. The air pressure, required to force air through a bed of grain, is dissipated continuously due to friction and turbulence. In order to overcome this resistance, applying a fan is necessary and these fans must develop enough pressure to overcome this resistance and move air through the crop. The energy demand for running the fan depends highly on the imposed pressure drop. Airflow resistance of agricultural products is typically presented in the form of pressure drop per unit depth of material. This is the form of presentation in ASAE Standard D272.3 (ASAE Standards, 2001). The most common approach used in estimating pressure drop through grain or seeds is reference to empirical curves relating airflow and pressure drop (Grama *et al*., 1984). The pressure drop depends on a number of the product and environment factors such as airflow rate, bed depth, fill method, presence of foreign materials, moisture content and surface and shape characteristics of the products (Dairo and Ajibola, 1994; Agullo and Marenya, 2005).

Luffa cylindrica commonly called sponge gourd, vegetable sponge, bath sponge or dish cloth gourd is a member of Cucurbitaceae family. It is a crawling plant that grows in the wild or on abandoned buildings, fenced walls in town and villages. The seeds can be roasted as a snack, or pressed to produce oil. The seeds are used for extraction of industrial oil (Bal *et al.,* 2004), and its use as biodiesel is now gaining wide acceptance because of the low CO_2 emission of the biodiesel produced from it and other considerations (Ajiwe *et al*., 2005). To successfully maximise the oil yield of the seed, there is need for appropriate postharvest processing especially drying and storage which are key operation in achieving maximum seeds quality. The effects of the process parameters on air flow resistance have been closely reviewed by several researchers for a number of materials including grains (Shedd, 1951 and 1953; Hukill and Ives, 1955; Jayas *et al*., 1987; Sokhansanj *et al*., 1990; Li and Sokhansanj, 1994; Dairo and Ajibola, 1994; Giner and Denisienia, 1996; Chung *et al*., 2001), parchment Arabica coffee (Agullo and Marenya, 2005), chickpea (Masoumi and Tabil, 2008), apples and chicory roots (Verboven *et al*.,2004), rape (Patil and Ward, 1988), and pistachio nuts (Kashaninejad and Tabil, 2009), however, information is scarce on the engineering and scientific data about the airflow resistance of the luffa seed. The objective of this study was to determine the airflow resistance of bulk *Luffa cylindrica* in a bulk column as affected by airflow rate, moisture content, bed depth and bulk density and obtain an appropriate model for predicting airflow resistance of *Luffa cylindrica* seeds.

Airflow resistance models

Data obtained from experimental runs are usually analysed by means of Shedd (1953) and Hukill and Ives (1955) equations. Both models have been widely used because they were found to fit many experimental data sets. However, the constants in these equations have a purely empirical nature, without physical meaning (Kenghe *et al*., 2011).

An alternative expression according to Verboven *et al*. (2004) is the model of Ergun (1952), originally developed for packed beds of uniformly sized spheres. The Ergun equation is based on fluid-dynamic principles (Kashaninejad and Tabil, 2009). Ergun model included the influence of the porosity, particle diameter, air density, and viscosity. According to the equation, the total energy loss in a packed bed should be treated as the sum of the viscous and kinetic energy losses. His original equation is given by Equation (3) (Garg and Maier, 2006):

$$\frac{\Delta P}{L} = A(Q)^{B} \qquad (1)$$

Where,

$\Delta P/L$ is pressure drop per unit depth of material (Pa/m)

Q is airflow rate in $m^3s^{-1}\ m^{-2}$,

A and B are experimentally determined constants

The model constant a, b have been related to moisture content and bulk density for seeds as reported by Dairo and Ajibola (1994).

$$\frac{\Delta P}{L} = \frac{CQ^2}{\mathrm{In}(1 + DQ)} \qquad (2)$$

Where,

C and D are constants for a particular grain. This equation is applicable over a wide airflow range of 0.01 to 2.0 $m^3s^{-1}m^{-2}$ (Dairo and Ajibola, 1994). Both the models have been widely used because they found to fit many experimental data sets.

$$\Delta P = \frac{A\ (1-\varepsilon)^2}{G_l\ \ ^2\varepsilon^3} Q + \frac{B\ (1-\varepsilon)}{G_l\ \ ^3} Q^2 \qquad (3)$$

Where: A and B in Erguns Equation are dimensionless empirical constants. At the given environmental condition and product, air viscosity(μ), air density(ρ), porosity of bed (ε) and geometric mead diameter (GDM) are constants.

For simplicity of use, factors other than air flow rate can be lumped in two parameters for each agricultural material according to Hunter (1983), Giner and Denisienia (1996). The simplified Ergun Equation is given by Equation (4)

$$\frac{\Delta P}{L} = E\quad + FQ^2 \qquad (4)$$

where E and F are experimentally determined constants which include the effect of fluid properties. Since the physical properties of the fluid and the product were considered in the Ergun equation, more realistic results could be expected.

Empirical relationship between airflow resistance and experimental variable using standard stepwise non-linear regression techniques have also been used by Siebenmorgen and Jindal (1987) on rough rice, Haque *et al*. (1978) on corn, Sorghum and wheat, Dairo and Ajibola (1994) on Sesame seeds, and Chung *et al*. (2001) on grain sorghum and rough rice. Sacilik (2004) used the equation to describe the pressure drop of poppy seeds, Agullo and Marenya (2005) to describe the pressure drop of parchment coffee, and Kenghe *et al*. (2011, 2012) to predict the pressure drop of lathyrus and soybean. The relationship is of this form of Equation 5

$$\Delta P = aQ^2 + b\quad\quad + c_l \qquad (5)$$

Where ΔP is the pressure drop (Pa/m),

Q is the airflow rate ($m^3s^{-1}m^{-2}$),

M is the moisture content (percentage wet basis),

B is the bulk density (Kg/m^3),

a,b,c, are model constants.

This relationship has been found to allow comparison of various parameters. Airflow rate (Q) was included as an overall multiplier in order to ensure that pressure drop was not predicted at zero airflow.

The Equation has been shown to predict adequately the effects of moisture content, airflow rate, bulk density on airflow resistance. (Dairo and Ajibola, 1994)

MATERIALS AND METHODS

Sample and Sample preparation

Sponge gourd fruits (*Luffa cylindrica*) were collected from the wild and abandoned buildings in Epe, Ikorodu and Oyo (all located in south western Nigeria) during the dry season also called "Harmattan" season between November and March in Nigeria. During this period, the fruits of *Luffa cylindrica* get dried up for harvesting. The cucumber shaped fruits has fibre meshed which holds the seeds. The gourds were opened and the fibre sliced into half, shaken to release the enmeshed black seeds. The seeds were later freed of impurities by manual sieving.

The initial moisture content of the sample was determined by using the standard oven method (AOAC, 2002). 30g samples were dried in a conventional oven at 130°C for 6 hours as recommended by Young *et al*. (1982) for seed with high oil content. The weight was monitored until there was no appreciable change in weight. It was then calculated using equation (6) as described by Norimi *et al*. (2012)

$$M\ (\%) = \frac{M_W - M_D}{M_W} \times 100 \qquad (6)$$

Where

MC is the moisture content in percentage

M_W is the weight of sample before drying in grams

M_D is the weight of dried sample in grams

Airflow Test Apparatus

The resistance to airflow through bulk Luffa seeds was measured using an experimental apparatus fabricated at the Department of Agricultural Engineering workshop as shown in Fig 1. Similar apparatus has been used to study pressure drop across bed depth and modified by several researchers such as Dairo and Ajibola (1994), Ray *et al.* (2004), Jekayinfa (2006), Kashaninejad *et al.* (2009), Shahbazi (2011), Kenghe *et al.* (2011). It comprised of a variable centrifugal fan, vertical air duct, airflow straighteners, pressure drop measurement system, instrumentation for airflow measurement, a plenum chamber, perforated sheet plate, test column and pressure taps.

Experimental Procedure

Luffa seeds samples were cleaned and allowed to equilibrate in the ambient condition for 6 hours as described by Dairo and Ajibola (1994) before pressure drop measurements. The pressure drop was measured at seven airflow rates (0.11, 0.13, 0.15, 0.18, 0.22, 0.27 and $0.32 m^3s^{-1}m^{-2}$), three moisture levels (9.98%wb, 13.5%wb, 16.5% wb), three bulk densities obtained with loose, medium and densely packed *Luffa* seeds at this respective order, and four bed depths (200, 400, 600 and 800 mm) measured to the top of the test column. The test column was filled with the seed samples up to 1000mm height and air was supplied to the system by a centrifugal fan (C.A.T NOVA mil APF 25) driven by a 1.1kw motor, via the horizontal air duct connected to the plenum, and delivered to the test column through the perforated sheet. The airflow rate in the air duct was measured with Hot wire anemometer (Kanimax Model: A004), the anemometer probe was inserted 10 cm after the straightening tube in the duct to measure the air velocity profile. Volumetric airflow was computed from the measured velocity and the cross sectional area of the tube.

As the air passes through the test column, the pressure drops between the first tap (located at 50mm above screen plate chosen as the reference) and all the other taps were measured using an inclined manometer, (made with 10mm diameter

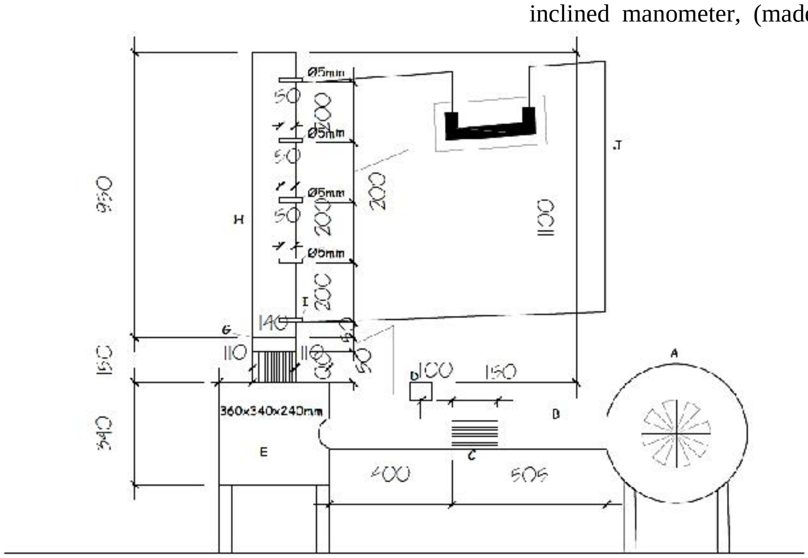

Fig. 1. Airflow Resistance Apparatus for airflow resistance
A, variable speed fan; B, horizontal air duct; C, airflow straightener; D, anemometer; E, plenum chamber; G, perforated sheet; H, test bin; I, pressure taps; J, inclined manometer

glass tube inclined at 120^0 to the horizontal), connected across the reference tap and other taps and were recorded. The experiment was repeated in triplicates to check the reproducibility of results. The airflow resistance was evaluated as static

The test column

The test column consisted of a cylindrical container constructed from a galvanised steel of 1m long with an internal diameter of 0.14m.

pressure drop per unit distance parallel to the direction of airflow as shown below in Equation (7).

$$A = \frac{\Delta P}{L} \qquad (7)$$

Where AR is the Airflow Resistance

ΔP is the Pressure Drop

L is Distance parallel to the direction of airflow

Seed Conditioning

The initial moisture content of the seeds 9.98% (wb) served as the first moisture level. Higher Moisture levels were obtained by adding calculated amount of tap water to the grains, using Equation (8) and stirred at intervals to ensure uniform rewetting so as to bring the samples to the desired moisture contents of 13.5 and 16.5% (w.b) respectively. (Aderinlewo *et al*., 2011)

$$Q = \frac{A(b-a)}{(100-b)} \qquad (8)$$

Where

A is the Initial mass of the sample, g

A is the Initial moisture content of the sample,% wet basis (w.b.)

B is the Final (desired) moisture content of sample % w.b.

Q is the Mass of water added to be added, g

The samples were then sealed in separate polyethylene bags and stored in cold storage at 5ºC for 5days. The conditioned test samples were removed from the refrigerator and left at room temperature for 6 hours so as to equilibrate it with the ambient temperature before use.

Bulk density

In order to determine the effect of the bulk density on the resistance to airflow of *Luffa cylindrica* seeds, three packing method, namely, loose, medium and dense, was used. For the loose fill, seed samples were poured freely into a funnel raised by 20 mm above the test column as described by Shedd, (1955) and as employed by Jekayinfa (2006) and Kenghe *et al*. (2011). Filling was done until the height of the seeds in the test column was 1000 mm. No compaction was done on the seeds in the column. Medium and dense filled method was obtained by a method described by Dairo and Ajibola (1994), Nimkar and Chattopadhyay (2002), Sacilik (2004) and Shahbazi (2011). The test column was loosely filled up to 1000 mm by adequate quantity of the test samples, then, the bulk density was gradually increased to a desired level by tapping the side of the column with a rubber hammer 30 times for medium, and 60 times for dense bulk density. By tapping the test column, the height of the seeds reduced, thus increasing the packing and no other seed samples added.

Bed depth

To determine the effect of the bed depth of Luffa seeds on the resistance to airflow, pressure drop was measured at four different depths of 200, 400, 600 and 800 mm from the top of the seed column. The first tap above the screen floor of the test column was chosen as the reference; the pressure differences between the first tap and all the other taps were measured and recorded.

Airflow rate

To study the effect of airflow rate on the airflow, the test column was filled with the seed samples up to 1000 mm height and Pressure drop through bulk Luffa seed was measured at seven airflow rates varying from 0.11 to 0.32 $m^3s^{-1}m^{-2}$ (0.11, 0.13, 0.15, 0.18, 0.22 and 0.32 $m^3s^{-1}m^{-2}$) for different test conditions. As a reference, the normal rates for drying grain range from 0.02 to 0.7$m^3s^{-1}m^{-2}$ (Ray *et al*., 2004). The terminal velocity of the seed was also put into consideration.

Selected Models

Several empirical and theoretical models have been developed relating pressure drop to airflow. In order to determine the best fit model to describe the relationship between the pressure drops to airflow of Luffa seeds. The Shedd, Hukill, and Ives, Ergun and Empirical model given by Equations (2), (3), (5), and (6), respectively were fitted to the experimental data.

Data Analysis and Modelling

The models (Shedd, Hukil & Ives and Ergun) were fitted to the pressure drop data of *Luffa cylindrica* seeds using the non-linear regression procedure. Empirical model was also obtained by relating experimental factors to the pressure drop using non-linear procedure. Evaluations of selected models were based on coefficient of determination (R^2), and root mean square error (RMSE).

RESULTS AND DISCUSSION

Airflow Resistance of Luffa Seed

Table 1 presents the experimental data for luffa seed at different moisture content airflow rate and bulk densities. Airflow Resistance of seeds is usually plotted on log-log basis as presented by the ASAE standard. Figures 2, 3, and 4 presents a typical Log-Log plot of airflow resistance across a bed of Luffa seed for loose, medium and densely packed beds. It was observed that there was increase in pressure drop as bed depth increased along the drying bed.

The effect of bulk density can also be shown from Fig 5, there was an increase in airflow resistance as bulk density increased from loose fill to densely packed beds.

Table 1. Pressure drop Across bin of luffa seed at various moisture content, airflow rate and bulk density

Airflow rate ($m^3/s.m^2$	Moisture content (% wet basis)								
	9.98			13.5			16.5		
	Bulk density(kg/m^3)								
	BD1	BD2	BD3	BD1	BD2	BD3	BD1	BD2	BD3
0.11	1.917	2.667	3.208	1.501	2.125	2.167	1.292	1.917	2.208
0.13	2.542	3.083	3.501	1.750	2.542	2.375	1.792	2.208	2.375
0.15	3.375	3.708	4.792	2.083	2.833	2.542	2.083	2.458	2.792
0.18	4.250	4.583	6.125	2.542	3.208	3.501	2.667	3.333	3.292
0.22	5.208	5.751	7.292	3.667	3.875	4.125	3.458	4.000	4.208
0.27	7.583	8.375	8.417	4.417	5.292	5.708	4.751	5.833	6.292
0.32	9.417	9.792	9.167	6.083	6.292	6.792	5.583	6.750	7.292

Modeling of Pressure Drop Data

The result of fitting the three selected models is presented in Table 2 to 4. These models were evaluated based on the coefficient of determination (R^2), Root Mean Square Error (RMSE), prediction values with respect to the measured values (e) for the full airflow range of 0.11 to 0.32 $m^3s^{-1}m^{-2}$; various moisture contents for the loose, medium and dense fill method respectively.

The values for R^2 obtained from Shedd model ranged from 0.9612 to 0.9958, with RMSE ranging from 0.02815 to 0.18582, for different experimental conditions (Table 2). These values for Hukill and Ives model ranged from 0.9574 to 0.995, MSE of 0.012526 to 0.20817 (Table 3), while corresponding values for Ergun's model ranged from 0.966 to 0.995, RMSE of 0.01371 to 0.031217 (Table 4). It can be stated in general that the R^2 values were greater than 0.95% for all the models, indicating that the three models were acceptable for predicting pressure drop across bulk Luffa seed beds.

However, the Shedd's model gave a highest R^2 value, lowest RMSE value compared to the other models. Therefore, Shedd's model was considered as best model for predicting pressure drop through bulk Luffa seed beds in all the cases.

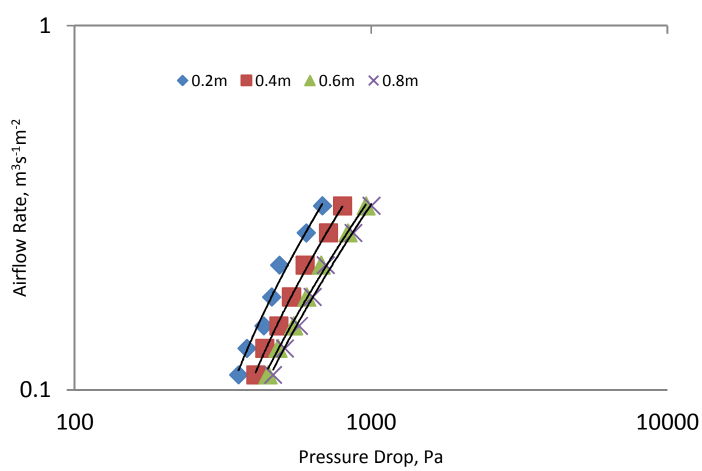

Figure 2: Airflow resistance on of Luffa seed at moisture content 9.98% (wb)

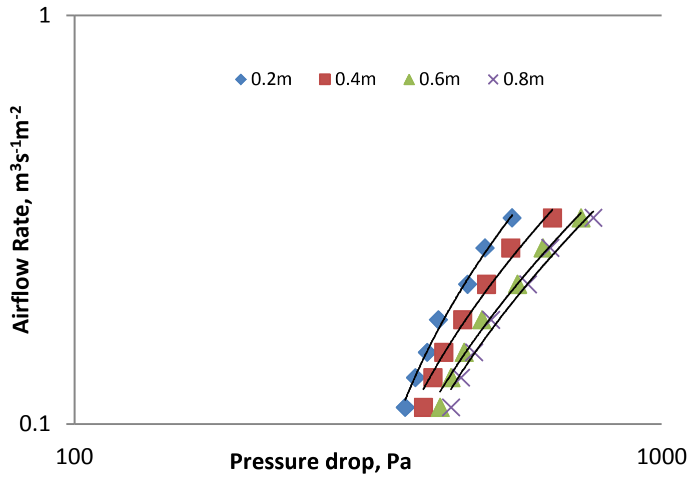

Figure 3: Airflow resistance on of Luffa seed at moisture content 13.5% (wb)

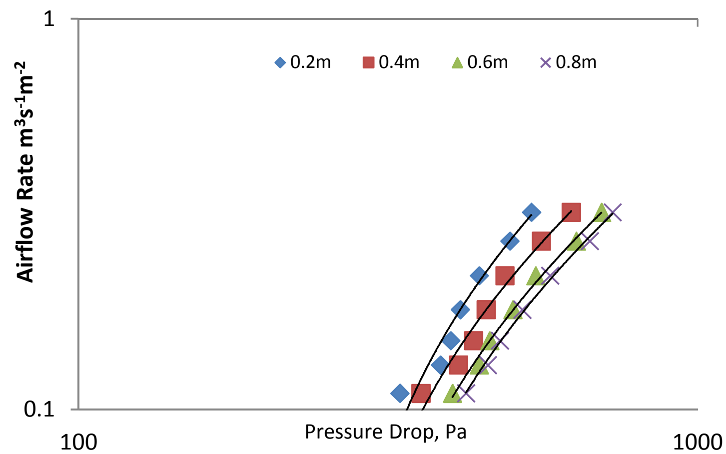

Figure 4: Airflow resistance on of Luffa seed at moisture content 16.5% (wb)

As observed from Table 5, the value of Shedd's parameter A decreased with moisture content at all the fill methods studied. This is a corroboration of the negative effect of moisture content on pressure drop (Shahbazi, 2011).

Also at low moisture content level, (9.98% wb), the value of parameter A reduces with density (filling methods) while it increased with density (filling method) at a higher moisture level of 16.5% (wb).

The effect of moisture content on parameter C of the Hukill and Ives is presented in Table 6. At the loose fill method, the parameter C and D decreased in value with increasing moisture content level, however, at a higher density of dense fill method, both parameters reduced with increasing values of moisture content.

The estimated values of the Ergun model parameter E generally reduced with increasing moisture content for all methods of fill considered (Table 4). The parameter F generally decreased with moisture content from loose and medium fill methods but increased in value when the method of fill was dense (Table 4).

Table 2: Estimated parameters and comparison criteria of Shedd model (Eq. (2)) at various moisture contents and fill methods

FILL METHOD	MOISTURE CONTENT(%WB)	PARAMETERS A	B	R^2	RMSE
LOOSE	9.98	48.80	1.44	0.996	0.02797
	13.5	28.49	1.38	0.991	0.02231
	16.5	25.56	1.32	0.996	0.02815
MEDIUM	9.98	43.55	1.30	0.992	0.0517
	13.5	20.78	1.06	0.988	0.02515
	16.5	29.19	1.27	0.989	0.03193
DENSE	9.98	28.28	0.94	0.961	0.18582
	13.5	26.16	1.18	0.990	0.02815
	16.5	31.368	1.27	0.982	0.0613

Table 3: Estimated parameters and comparison criteria of Hukill and Ives model (Eq. (3)) at various moisture contents and fill methods

FILL METHOD	MOISTURE CONTENT(%wb)	PARAMETERS C	D	R^2	RMSE
LOOSE	9.98	149.94	12.60	0.995	0.21093
	13.5	76.77	8.58	0.992	0.18865
	16.5	59.49	5.93	0.994	0.01252
MEDIUM	9.98	96.97	5.34	0.992	0.04948
	13.5	13.13	0.75	0.989	0.02282
	16.5	58.86	4.38	0.989	0.03135
DENSE	9.98	3.03	0.10	0.957	0.20817
	13.5	39.31	2.51	0.990	0.02516
	16.5	65.38	4.61	0.983	0.05543

Empirical Model

The result obtained in fitting the data to the selected empirical model is presented in Table 5. The R^2 value was 0.943 with a Root Mean Square Error of 0.2642, the model parameter were obtained and the model in the form of Equation 9. Analysis of variance was also used to test for the significance of the model in the prediction of static pressure drop of Luffa seeds in a bulk column.

The ANOVA gave an $F_{critical}$ value of 3.918 compared with the F value of 0.0041. This indicated that the empirical model is significant enough to predict the static pressure drop of the seeds.

$$\Delta P = 19.6109Q^2 + (-0.6914)M + 0.06914B \quad (9)$$

Table 4: Estimated parameters and comparison criteria of Ergun type model (Eq. (5)) at various moisture contents and fill methods

FILL METHOD	MOISTURE CONTENT (%wb)	PARAMETERS E	F	R^2	RMSE
LOOSE	9.98	13.71	50.14	0.995	0.03217
	13.5	9.750	27.83	0.992	0.01781
	16.5	10.66	22.65	0.994	0.01371
MEDIUM	9.98	19.06	37.88	0.992	0.04986
	13.5	17.52	6.240	0.989	0.02271
	16.5	13.84	24.07	0.990	0.03160
DENSE	9.98	33.72	-12.32	0.966	0.16900
	13.5	15.88	17.08	0.991	0.02493
	16.5	14.72	26.29	0.984	0.05401

Table 5: The parameter estimates for the empirical model

Model coefficient	a	b	C	R^2	RMSE
	19.61089	-0.69136	0.065156	0.943	0.2642

CONCLUSIONS

The airflow resistance of bulk sponge gourd seeds (*Luffa cylindrica*) as affected by seed moisture content, bed depth, bulk density and airflow rates was investigated. The data obtained was fitted to established shed, Hukil and Ives, and Ergun models to obtain the model parameters at the levels of experimental factors studied. An empirical model commonly used for airflow resistance containing airflow, moisture content and bulk density as model factors was also fitted with the experimental data to obtain the model parameter values. Based on the results obtained from the study, the following conclusion could be drawn.

i. The resistance to airflow of *Luffa cylindrica* seed increased with increasing airflow rate, bed depth bulk density but decreased with increasing moisture content.

ii. All selected models were adequate for predicting airflow resistance of *Luffa cylindrica* with coefficient of determination (R^2) values greater than 0.950. However, shedd's model gave a highest value for coefficient of determination (0.9958) and lowest values for RMSE (0.02815). It was considered the best fit model for predicting pressure drop across *Luffa cylindrica* seeds with the experimental factors range considered.

iii. The parameters commonly used to predict pressure drop through bulk seed as affected by airflow rate, bulk density and moisture content was also fitted to *Luffa cylindrica* data and the model parameter obtained. The model fitted the experimental data reasonably well with R^2 value of 0.943.

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