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Advancing Coconut Dehusking Technology: A Dimensional Analysis-Based Parametric Model for Local Production

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ABSTRACT

Effective dehusking is essential to the coconut industry's value chain, which is still a major industry in many tropical economies. Using dimensional analysis based on Buckingham's π theorem, this study proposes a novel mathematical model to forecast the dehusking efficiency of a locally made coconut dehusking machine. The model was created to help regional producers optimize their equipment for better output. The model was validated using experimental study data, showing a maximum correlation coefficient (R2 = 0.388) between the predicted and measured dehusking efficiencies. Despite this moderate correlation, the model showed strong applicability, enabling dehusking efficiency estimates with an astounding accuracy of up to 89.5%. This degree of accuracy indicates that engineers and manufacturers looking to improve coconut processing technologies may find it useful. By reducing material waste and boosting productivity in regional agricultural contexts, the work's implications go beyond simple efficiency gains and support sustainable production methods. Given the coconut's economic significance, the model is a useful tool for supply chain participants, especially in environments with limited resources. This research opens the door for future advancements in agricultural machinery design by using dimensional analysis to better understand dehusking mechanisms. All things considered, the creation and verification of this parametric model mark a critical advancement in the technological capacity of regional coconut production, which will ultimately promote sustainability and economic growth.

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Introduction

The coconut fruit, classified as a fibrous drupe, consists of various layers that impart its distinctive architecture and multifunctionality. From the exterior to the interior, it is characterized by a thin hard layer known as the exocarp, a more substantial fibrous component referred to as the mesocarp or husk, a robust protective shell identified as the endocarp, a creamy inner substance termed endosperm, and a sizable void filled with liquid recognized as coconut water. Immature specimens of coconuts commonly display a green exocarp, and there is considerable variation in the morphology and dimensions of coconuts among different varieties and populations, exhibiting shapes that range from elongated to almost spherical configurations. Coconut palms possess the capability to yield fruits continuously throughout the year, with a mean production of 50 to 80 fruits per individual tree annually [1].

Coconuts are esteemed for their multifaceted applications, making substantial contributions to the realm of global agriculture. In the year 2020, worldwide coconut production was approximately 62 million metric tonnes, with Indonesia, India, and the Philippines collectively representing 75% of this total output. Nigeria, positioned as the 19th largest producer of coconuts on a global scale, reported an annual production volume of 224,184.26 tons [2]. In light of Nigeria's extensive arable lands and conducive tropical climate, there exists considerable potential for the enhancement of coconut production.

The dehusking operation is integral to the processing of coconuts, as it involves the detachment of the coconut husk from the shell. This essential procedure can be executed through manual, mechanical, or automated means [3]. Traditional practices, such as employing a cutlass, are associated with notable disadvantages, including inefficiency, elevated labour costs, and safety hazards linked to manual handling [4,5]. As a result, the innovation of coconut dehusking machinery is imperative for the enhancement of productivity and sustainability within the coconut processing sector. Locally manufactured machines provide economical solutions for smallholder farmers, integrating components such as structural bases, hoppers, chutes, shafts, bearings, pulleys, gears, electric motors, and drums, which are predominantly fabricated from mild steel and polyester (PET) fibers. The effectiveness of dehusking operations is vital for the optimal utilization of resources, as it represents the proportion of husk effectively separated from the shell. Elevated dehusking efficiencies not only diminish waste but also lower production costs, thereby augmenting the overall sustainability and economic feasibility of the operation.

This investigation employs dimensional analysis, specifically the Buckingham π theorem, as a foundational methodology for formulating a mathematical model aimed at predicting the efficiency of coconut dehusking machinery. The π theorem asserts that all physically significant equations must possess dimensional homogeneity, facilitating the reduction of independent variables in complex scenarios (Sonin, 2001). The application of dimensionless analysis has demonstrated efficacy in modelling the operational performance of coconut dehusking machines [6-8]

In this manuscript, we will elucidate the theoretical foundations of Buckingham's π theorem and its relevance to the design of coconut dehusking equipment. The methodology for the parametric modelling process will be delineated, followed by a presentation of the findings derived from both simulation and experimental investigations.

Literature Review

A review of relevant studies and research papers on coconut dehusking machines and parametric modelling based on Buckingham pi theorem is as follows;

Review on Coconut Dehusking Machines

Did research on a coconut dehusking machine which was developed and evaluated in terms of dehusking performance [9]. The model consists of different component assembly parts such as speed reduction, transmission, coconut base, dehusking blade, frame, and control system. It is powered by a 7.5 hp gasoline engine and with an average output capacity of 240 coconut per hour. The cutting tooth initiates the initial penetration of the blades while the side face angle can assist better piercing or shearing action on the coconut husks. The coconut base can be moved upward or downward and can accommodate different coconut sizes. The effects of different factors which include the machine's crankshaft speed, coconut size, and blade side angle on the response variables were investigated. Data obtained from the response variables mostly fit the linear, cross-product, and quadratic regression models. The superimposed contour plots of different factors generated an optimum region and yielded a dehusking performance with a force requirement of 109.59 N, power consumption of 6.41kW, dehusking time of 3.34 minutes, dehusking rate of 4 nuts per minute, and dehusking efficiency of 85.23 %

Review on Parametric Modelling Based on Buckingham pi Theorem of Machines

Developed a mathematical model for predicting the peeling efficiency of a cassava peeler using a dimensional analysis based on Buckingham's pi theorem [10]. The model was validated using data from experimental studies which revealed a maximum coefficient of correlation of R2 = 0.8366 between the measured and predicted values. The developed model proved appropriate in estimating the peel removal efficiency for a cassava peeler by up to 83.66%. There was no significant difference between the experimental and predicted values at a 0.05 significance level.

Similarly, developed a mathematical model for predicting the shelling efficiency of an impact snake gourd seed decorticator which was presented using dimension analysis based on Buckingham's pi theorem [11]. Experimental verification of the models was conducted by comparing the theoretical predictions with estimates from the representation of conventional methods. A high coefficient of correlation was found between the predicted and the experimental values (98.45% for the effect of moisture content on decortication efficiency; 99.69% for the impact of hammer diameter on decortication efficiency and 97.35% for the impact of hammer speed on the decortications efficiency) showing that the model is appropriate

Methodology

Coconut Dehusker CAD and Parametric Model Development

The engineered coconut dehusking apparatus comprises several essential elements that collaboratively function to effectively detach the husk from coconuts in a mechanized fashion. The primary objective in the creation of this apparatus was to develop a cost-effective and user-friendly solution that mitigates the constraints of traditional manual dehusking techniques presently employed by smallholder coconut cultivators in Nigeria [12]. The structural chassis of the apparatus forms its foundational component and is designed to securely retain all other elements in position throughout operational processes. The chassis needed to possess the capacity to endure the forces associated with dehusking hundreds of coconuts daily over prolonged durations of operation. The chassis features a modular open design fabricated from mild steel angles and flat bars, which are readily and economically accessible within the local market. Angles were welded at the intersections and joints to construct a robust framework measuring 750mm in length, 500mm in width, and 592mm in height. The apparatus is powered by a 1.5-horsepower electric motor situated within the chassis beneath the hopper. The selection of the electric motor was predicated on its availability, minimal maintenance costs, and the convenience of replacing components if necessary. This motor actuates the operation of the apparatus through a V-grooved pulley wheel and poly-V belt that connects to the primary driveshaft located below. The driveshaft subsequently transmits torque to the dehusking components via gears, ensuring a reliable transfer of rotational force. Two parallel cylindrical drums extend horizontally across the midpoint of the chassis, functioning as the principal dehusking units. Each drum possesses a diameter of 320mm and was manufactured from a 6mm thick mild steel hollow bar. Uniformly distributed along their outer surfaces are rows of 10mm long stainless-steel spikes that protrude radially outward at a 15-degree angle to facilitate the disruption of the husk fibers. When engaged, the drums counter-rotate in opposing directions, efficiently tearing away the husk in contact with the coconut. All fabrication was executed within a financial constraint of 250,000 NGN (168.69 USD), utilizing basic workshop tools and locally sourced materials to minimise expenses. Input from consultations with farmers was integrated into the design of the apparatus to ensure its practicality and feasibility for their agricultural operations. The control mechanism of the apparatus is designed to be uncomplicated, featuring an on/off switch and safety measures incorporated into the control panel. In summary, this mechanized solution aspires to surmount the significant limitations of manual dehusking in a sustainable manner that is appropriate for resource-constrained farmers. Figure 1 shows the CAD model and the locally fabricated coconut dehusking machine

Figure 1: CAD Model and the Locally Produced Coconut Dehusking Machine [6]

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Dehusking Efficiency Model

Predictive equations for evaluating the performance of coconut dehusking machines were developed using the dimensional analysis method [6-8]. The independent variables affecting the machine's dehusking efficiency are Dehusking speed, dehusking drum diameter, spike length, dehusking drum length, and spike angle. The equations were developed using the [M], [L], [T] basic system of dimensions.

Table 1: Basic Dimensions of Variables for Dehusking Efficiency Model

S/N	Variable	Symbol	Unit	Dimensional unit
1	Dehusking efficiency	DH_{eff}	kg/s	-
2	Dehusking speed	ω_h	rev/s	T^{-1}
3	Drum length	L_h	mm^2	L
4	Drum diameter	D_h	mm	L
5	Spike length	d	mm	L
6	Spike Angle	θ	°	Dimensionless

$DH_{eff} \propto (\omega_h, L_h, D_h, d, \theta)$

$DH_{eff} = f(\omega_h, L_h, D_h, d, \theta)$ …………….. Eqn 3.1

Total number of variables = 6

Number of fundamental dimensional units = 2

Number of dimensionless groups = 6 – 2 = 4

Therefore, there will be three π-terms namely π_1, π_2, π_3 and π_4

$\pi_1 = CDH(\pi_2, \pi_3, \pi_4)$ .... Eqn 3.2

Where;

C_{DH} = Dehusking efficiency constant

π_1, π_2, π_3 and π_4 = *pi* terms to be determined

The repeating variables used are ω_h and L_h

Table 2: Dimensional Matrix of Variables for the Dehusking Efficiency Model

Dimensional unit	Variables					
	DH_{eff}	ω_h	L_h	d	D_h	θ
		a	b			
M	0	0	0	0	0	-
L	0	0	1	1	1	-
T	0	-1	0	0	0	-

Combining the dependent variable and the repeating variables to form the first Pi term; that is,

$\pi_1 = DH_{eff}\, \omega_h^a L_h^b$................ Eqn 3.3

Since the combination is dimensionless, it follows that,

$[T^{-1}]^a \; [L]^b = L^0 T^0$

For L, b = 0

For T, – a = 0

Therefore, b = 0 and a = 0 Hence

$\pi_1 = DH_{eff}\, \omega_h^0 L_h^0$........................... Eqn 3.4

π_1 is obtained as given in eqn. above

$$\pi_1 = DH_{eff}$$

To obtain π_2

$\pi_2 = d\omega_h^a L_h^b$.......................... Eqn 3.5

Since the combination is dimensionless, it follows that,

$[L] \; [T^{-1}]^a \, [L]^b = L^0 T^0$

For L, 1 + b = 0

For T, -a = 0

Therefore, a = 0 and b = -1 Hence

$\pi_2 = d\omega_h^0 L_h^{-1}$..................... Eqn 3.6

π_2 is obtained as given in eqn. above

$$\pi_2 = \frac{d}{L_h} \quad \text{.................... Eqn 3.7}$$

To obtain π_3

$\pi_3 = Dh\, \omega_h^a L_h^b$................. Eqn 3.8

Since the combination is dimensionless, it follows that,

$[L] \; [T^{-1}]^a \, [L]^b = L^0 T^0$

For L, 1 + b = 0

For T, -a = 0

Therefore, a = 0 and b = -1 Hence

$\pi_3 = Dh\, \omega_h^0 L_h^{-1}$................ Eqn 3.9

π_3 is obtained as given in eqn. above

$$\pi_3 = \frac{D_h}{L_c} \quad \text{.............. Eqn 3.10}$$

To obtain π_4

$\pi_4 = \theta\omega_h^a L_h^b$.................. Eqn 3.11

Since the combination is dimensionless, it follows that,

$[1] \; [T^{-1}]^a \, [Lh]^b = L^0 T^0$

For L, b = 0

For T, -a = 0

Therefore, a = 0 and b = 0, Hence

$\pi_4 = \theta\omega_h^0 L_h^0$............... Eqn 3.12

π_4 is obtained as given in eqn. above

$\pi_4=\theta$ ……............... Eqn 3.13

Considering that the multiplication and division of dimensionless quantities have no effect on the final analysis results the required relationship is therefore obtained by combining the π-terms in eqn. 3.7, 3.10 and 3.13 [13].

Since,

$\pi_1=CDH\ (\pi_2,\pi_3,\pi_4,)$................. Eqn 3.14

Let $\pi_5=\left[\frac{\pi_4}{\pi_2\times\pi_3}\right]$ .... Eqn 3.15

The required relationship is therefore obtained by combining the π-terms in equations 3.7, 3.10 and 3.13.

$$DH_{eff} = C_{DH}\left[(\theta) \div \left(\frac{d}{L_h} \times \frac{D_h}{L_h}\right)\right]$$

The equation can be arranged as given in (3.31).

$$DH_{eff} = C_{DH}\left(\frac{\theta(L_h)^2}{d \times D_h}\right) \quad \text{................... Eqn 3.16}$$

Determination of Dehusking Efficiency Constant

The determination of the efficiency constant C_{DH} involved the utilization of linearized expressions for π5 and π1 namely, $\left[\frac{\pi_4}{\pi_2\times\pi_3}\ and\ DH_{eff}\right]$ extracted from the developed model. To determine the dehusking efficiency constant, linear regression analysis of π1and π5was plotted which gave a coefficient of correlation of 0.388. This process was executed employing the method of least squares, a statistical technique, as elaborated by the works of [14]. However, as shown in Figure 2, the regression coefficient, R2, obtained was 0.388.

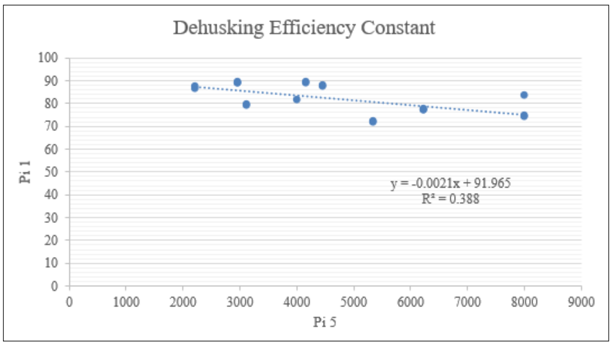

Figure 2: Determination of Dehusking efficiency Constant

Table 3: Result for Dimensional Analysis Pi Terms for Dehusking Efficiency

S/N	Dehusking Efficiency DH_{eff}	Spike Angle θ	Spike Length d	Drum Length L_h	Drum Diameter D_h	π_1	π_5
	%	Degrees	mm	mm	mm		
1	81.3	90	20	320	115	81.3	4006.957
2	76.9	70	10	320	115	76.9	6233.043
3	88.8	70	15	320	115	88.8	4155.362
4	87.2	50	10	320	115	87.2	4452.174
5	83.4	90	10	320	115	83.4	8013.913
6	87.1	50	20	320	115	87.1	2226.087
7	73.9	90	10	320	115	73.9	8013.913
8	89.1	50	15	320	115	89.1	2968.116
9	88.9	50	15	320	115	88.9	2968.116
10	89.2	70	15	320	115	89.2	4155.362
11	87.9	50	10	320	115	87.9	4452.174
12	79.6	70	20	320	115	79.6	3116.522
13	86.5	50	20	320	115	86.5	2226.087
14	77.6	70	10	320	115	77.6	6233.043
15	71.2	90	15	320	115	71.2	5342.609
16	77.1	70	10	320	115	77.1	6233.043
17	78.8	70	20	320	115	78.8	3116.522
18	89.5	50	15	320	115	89.5	2968.116
19	74.7	90	10	320	115	74.7	8013.913
20	72.2	90	15	320	115	72.2	5342.609

Results

Predictive models relating to the quality of the operating variables of the coconut dehusking machine were developd based on dimensional analysis and multiple regression analysis of experimental data. The model is:

Dehusking Efficiency (DH_{eff}) $C_{DH}\left(\frac{\theta(L_h)^2}{d\times D_h}\right)$

The coefficient of corelation (R^2) values indicated a very good fit of the models. These models allow the prediction of dehusking outputs under varying operational conditions without extensive experimentation. The machine can attain an efficiency of 89.5% with a spike angle of 50^0, spike length of 15mm, drum length of 320mm, and drum diameter of 115mm.

Design Validation

Validation of Dehusking Efficiency Model

The result of the predicted dehusking efficiency was calculated using dimensional analysis model equation while the measured value was obtained using equation $[DH_{eff} = \frac{weight\ of\ husk\ removed\ by\ machine\ (kg)}{weight\ of\ total\ husk\ (kg)} X100]$.

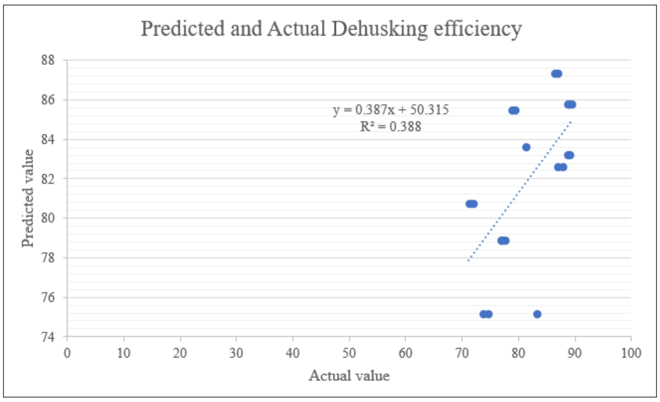

Figure 3: Relationship Between Predicted and Actual Dehusking efficiency

Figure 3 shows the graphical representation of the predicted and actual values of the experiment for the dehusking efficiency of the machine. The graph confirms a high similarity between the predicted and actual values for the dehusking efficiency investigation [15].

Conclusion

In conclusion, the parametric modeling of the locally produced coconut dehusking machine using the Buckingham Pi theorem has provided valuable insights into the de-husking process of coconut. By applying dimensional analysis and developing predictive models, a mathematical framework was introduced to predict the efficiency of the machine.

- This model equation, represented as (DH_{eff}) = $C_{DH}\left(\frac{\theta(L_h)^2}{d\times D_h}\right)$ for predicting the machine efficiency.
- An R^2 value of 0.388 was obtained from the analysis
- The optimization of variables such as drum length, spike angle, spike length, and drum diameter has the potential to significantly enhance the performance of the dehusking process.

The findings of this study contribute to the development of a robust and efficient model for coconut dehusking, which can lead to improved productivity and reduced waste. Further research can explore additional variables and conduct experiments to validate and refine the parametric model.

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