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Numerical and Experimental Investigation of Throughput Capacity in Cassava Peeling Processes

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ABSTRACT

This study aims to develop a theoretical model for predicting the throughput capacity of cassava peeling machines utilizing dimensional analysis based on Buckingham's π theorem. Six governing variables—machine throughput capacity, tuber angular speed, peeling tool speed, tuber mass, peel penetration force, and peeling time—were identified and expressed in terms of three fundamental dimensions (M, L, T). Application of the Buckingham π theorem therefore yielded three independent dimensionless groups, derived using tuber angular speed, peel penetration force, and peeling tool speed as repeating variables. These π terms formed the basis of the predictive throughput model, which was subsequently calibrated and validated against experimental data. The established model demonstrated a high coefficient of determination (R^2 = 0.9047), indicating a strong correlation between predicted and measured throughput capacities. Model performance was further evaluated using error-based metrics, with the selected model yielding low RMSE (0.00065 kg/s) and MAE (0.00049 kg/s), confirming its strong predictive accuracy.

1. Introduction

Cassava (*Manihot esculenta*) is a crucial root crop generally cultivated in subtropical and tropical areas, serving as an essential crop for millions of people [1]. Its adaptability to diverse climatic conditions and high carbohydrate content contribute to its popularity [2,3]. Beyond its importance as a source of food, cassava is also a vital raw crop for different utilization at the industrial level, among which are starch production, biofuels, and animal feeds [4-6]. However, the processing of cassava into consumable forms involves several labor-intensive steps, with peeling being one of the most critical and time-consuming operations [2].

Efficient mechanization in cassava processing can significantly alleviate the drudgery associated with post-harvesting tasks. Peeling, a vital step in this process, directly influences the recovery of the usable flesh and the overall quality of the end product [7]. Despite advancements in technology,

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peeling remains a global challenge due to several factors. One major issue is the high variability in tuber size and shape, complicating the design of universal peeling solutions [8,9]. Additionally, the bond that exist between the peels and the flesh varies among cassava varieties, leading to inconsistent peeling efficiency and increased waste. Moreover, the moisture level and texture of the tubers also influence the effectiveness of peeling methods. As noted by Krishnakumar *et al.,* [10], these challenges necessitate ongoing innovation in peeling technologies. Furthermore, Amuda and Alabdulrahman [11] emphasize the importance of cassava production in enhancing food security and facilitating industrialization and foreign exchange.

To optimize the performance of peeling systems, researchers utilize numerical modeling techniques to predict their functional behavior. Approaches such as numerical analysis [12-14] and computational fluid dynamics [15-19] help tackle complex challenges in the peeling process. However, empirical data is essential for validating theoretical models, highlighting the importance of experimental approaches in addressing practical challenges [12,20]. Mathematical modeling serves as a theoretical framework for representing real-world phenomena, often generating predictive insights. Techniques such as dimensional analysis simplify complex physical problems, aiding in the design and scaling of experiments [21]. While widely used in chemical and fluid dynamics, dimensional analysis is less prevalent in systems engineering. It provides a systematic method for organizing and interpreting results, facilitating the transition from models to prototypes [22].

Theoretical modeling in agricultural engineering has addressed various processes, including harvesting [23-25], sprayers [26-29], and food handling systems [30,31]. However, there is a scarcity of data on modeling the throughput capacity of a cassava peeler. Previous studies have explored related cutting processes, such as their impact on forage crops [32 & 33] and the efficiency of potato processing [34,35]. Dimensional analysis, particularly Buckingham's Pi theorem, has proven effective in developing predictive models across various engineering domains. Applications include micro-channel heat sinks [36], ball bearing parameters [37], and scaling-up simulation processes in fuel cells [38] and membrane distillation systems [39]. Researchers have utilized dimensional analysis through the Buckingham's π approach as an effective technique for estimating predictive equations for various systems, such as screw-conveyor models [40] and grain threshers [41]. In spite of alternative dimensional analysis methods, such an indicial method, Buckingham's π theorem remains a robust approach [22].

Despite the critical role of cassava in food security and industrial applications, significant challenges remain in the peeling process due to variability in tuber characteristics and the inefficiencies of existing mechanization methods. Current theoretical models are often limited in empirical validation, creating a gap in reliable predictive tools for optimizing cassava peeling systems. This research addresses this gap by developing a numerical framework using dimensional analysis, specifically employing Buckingham's π theorem. The objective is to establish a model for estimating the throughput capacity of a cassava peeler, thereby enhancing equipment performance and contributing to greater efficiency and reduced waste in cassava processing. The findings are expected to support ongoing innovations in peeling technology, ultimately benefiting the broader agricultural sector.

2. Methodology

2.1 Conceptual Approach

The performance and dimensions of a system are influenced by machine and crop parameters, analyzed through dimensional approach and similarity condition, which necessitate that the underline quantities exhibit dynamic similarity [42]. In constructing the model, the focus was on establishing the relationship between dependent and independent variables to identify which parameters impact system performance. Dimensional analysis was employed as a technique to determine the underlying effects in a physical scenario and to establish the functional relationships among them.

Dimensional analysis based on Buckingham's π approach ascertained that if there exist a functional correlation contained as m variables with n overall number of dimensions then in utilizing the dimensional approach, the functional relationship will involve m − n groups of dimensionless quantities [43].

Given that the functional relationship of the model consist of $x_1, x_2, \ldots \ldots \ldots x_m$ variables irrespective of which is dependent parameters. Hence, the functional relationship can be expressed as;

$$f(x_1, x_2, \ldots \ldots \ldots \ldots \ldots \ldots \ldots x_m) = 0 \quad (1)$$

If there exist n basic dimensions parameters altogether, then the procedure for dimensional approach will change the theoretical relationship into;

$$f_1(\pi_1, \pi_2, \ldots \ldots \ldots \ldots \ldots \ldots \ldots \pi_{m-n}) = 0 \quad (2)$$

In estimating pi's, the repeating variables are first identified as n, which must together involve the n basic dimensions;

$$\therefore \pi_1 = (y_1^{x11}, y_2^{x12} \ldots \ldots \ldots \ldots \ldots \ldots \ldots y_n^{x1n})y_{n+1} \quad (3)$$

$$\pi_2 = (y_1^{x21}, y_2^{x22} \ldots \ldots \ldots \ldots \ldots \ldots \ldots y_n^{x2n})y_{n+2} \quad (4)$$

$$\pi_{m-n} = \left(y_1^{x(m-n)1}, y_2^{x(m-n)2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots y_n^{x(m-n)n}\right)y_m \quad (5)$$

In expressing the underlying variables in the peeling system, there basic dimensions were used for each equation; the π were also identified while each of the basic dimensions is raised to power of zero [42]. The equations are then resolved by setting every basic dimension's exponent to zero.

2.2 Model Development Assumptions

In the development of the model, some simplifying assumptions were made;

- Tuber orientation, age and variations are considered negligible in the development of the model;
- Consideration was given to measurable design parameters; and
- The tuber is assumed to be cylindrical in shape with uniform moisture content

2.2 Development of the Theoretical Machine Throughput Capacity Expression

The stated assumptions assisted in minimizing the amount of parameters involved to the ones highlighted as they were assumed to have much effect on the throughput capacity of the cassava peeler and are quantifiable. The parameters include; tuber speed of rotation (ω), speed of peeling tool (λ), mass of tuber (m_t), peel penetration force (F), and time of peeling (t). The peeling tool speed (λ) represents the linear velocity of the peeling knife relative to the cassava tuber surface during peeling. It was controlled through the computer-vision–assisted actuator system and measured as the rate at which the peeling tool traverses the tuber surface (mm s^{-1}). This parameter governs the intensity of tool–tuber interaction and directly influences peel removal efficiency and throughput. The peel penetration force (F) on the other hand refers to the normal force required for the peeling tool to penetrate the cassava peel layer up to the cambium without damaging the edible flesh. It was determined experimentally as the force per unit tuber length (N mm^{-1}) acting at the tool–tuber interface during peeling. This variable characterizes the mechanical resistance of the peel and reflects varietal and material properties of the tuber. The tuber speed of rotation (ω) denotes the angular velocity at which the cassava tuber rotates against the peeling tool during operation. It was controlled by the drive mechanism and measured in revolutions per minute (rpm), influencing the frequency of tool–tuber contact and material removal rate. The mass of tuber (m_t) represents the total mass of an individual cassava tuber prior to peeling, measured using an electronic weighing balance. This variable accounts for size-related effects on throughput capacity and material load during peeling. The time of peeling (t) is defined as the duration required to completely remove the peel from a cassava tuber under specified operating conditions. It was measured using a stopwatch and reflects the combined influence of tuber properties and machine operating parameters on throughput.

After determining the primary factors influencing the machine throughput capacity, Eq. (6) describes the theoretical equation of model prediction.

$$T_{Cap} = f(F, \lambda, m_t, \omega, t) \quad (6)$$

Where T_{Cap} is the Machine Throughput Capacity

Utilizing the $[M], [L], [T]$ approach of dimension, Table 1 presents the dimensions of the system variables while Table 2 presents the dimensional matrix of the model. From Buckingham's π's approach [44] the dimensionless quantities (n) to be generated is expressed as;

$$n = V - x \quad (7)$$

Where:

V = Amount of variables available in the system = 6

x = Number of fundamental dimension specifying the variables = 3

Hence,

n = 6 – 3 = 3

Hence, three dimensionless quantities were generated, confirming the necessity of forming π_1; π_2; and π_3 in describing the system.

Hence, speed of tuber rotation(ω), peel penetration force (F) and speed of cutting tool (λ) were chosen as the set of criteria that would be used repeatedly since they included all of the main aspects of the performance criteria at hand and their combinations does not form a dimensionless quantity.

Having selected(ω), (F) and (λ) as the recurring sets, the exponents a, b and c are placed on them respectively so that when their product $\omega^a F^b \lambda^c$ divide the remaining variables, T_{Cap}, t and m_t, the dimensionless quantities π_1, π_2 and π_3 are generated as obtained in eq. 8 to 10 [45 – 47].

Table 1
Variables list with their dimensions

S/N	Variables	Symbol	Unit	Dimensions
1	Machine Throughput Capacity	T_{Cap}	kgs^{-1}	MT^{-1}
5	Peel penetration force per tuber length	F	kgs^{-2}	MT^{-2}
6	Peeling tool speed	λ	ms^{-1}	LT^{-1}
7	Mass of tuber	m_t	kg	M
8	Angular speed	ω	rpm	T^{-1}
9	Peeling time	t	s	T

Table 2
Dimensional matrix of the variables

S/N	Variable	Symbol	M	L	T
1	Machine Throughput Capacity	T_{Cap}	1	0	−1
2	Peel penetration force per tuber length	F	1	0	−2
3	Peeling tool speed	λ	0	1	−1
4	Mass of tuber	m_t	1	0	0
5	Angular speed	ω	0	0	−1
6	Peeling time	t	0	0	1

Hence,

$$\pi_1 = \frac{MTC\ \omega}{F} \quad (8)$$

$$\pi_2 = \frac{\omega^2 m_t}{F} \quad (9)$$

$$\pi_3 = \omega t \quad (10)$$

Merging the above equations to produce eq. (11), with dimensionless components and it is expressed as;

$$\pi_1 = f(\pi_2;\ \pi_3)$$

$$\therefore \frac{MTC\ \omega}{F} = f\left(\frac{\omega^2 m_t}{F}, \omega t\right) \quad (11)$$

Hence,

$$MTC = f(\omega m_t, Ft) \quad (12)$$

Eq. (12) illustrates the functional equation for the machine throughput capacity with the variables as an expression of two functional components; ωm_t, and Ft which are described in terms of P and Q respectively in Eq. (13)

$$MTC = f(P, Q) \quad (13)$$

2.4 Experimental Method

Twenty samples of fully grown two year old TME 419 variety of cassava tubers (Manihot Esculenta Crantz) harvested from Obafemi Awolowo University, Ile – Ife, Nigeria, Teaching and Research Farm were sorted into 10 samples after being completely cleaned of all contaminants to determine some physical characteristics of cassava tubers. A computer vision driven approach was utilized as a means for driving a peeling knife at a preset speed of 0.33mm/s which moves through a span of 0.2m and penetrating the tuber up to the peel thickness layer (Cambium) and peeling the tuber specimen which revolves against a fixed peeling tool. The mechanism was employed to provide precise control of peeling tool motion and penetration depth, thereby minimizing operator-induced variability during experimentation. This approach ensured consistent and repeatable operating conditions, making it suitable for validating the proposed dimensional analysis–based throughput model. The controlled experimental setup shown in Figure 1 also supports the assumptions adopted in the dimensional modelling framework.

Experimental results obtained from the peeling mechanisms are utilized in verifying the system throughput capacity. Some apparatus used in empirical analysis are described below;

Machine Throughput Capacity (T_{Cap}) Measurement: Machine throughput capacity was measured by weighing the mass of cassava to be peeled during process of peeling, to the time it takes to achieve peeling, it is expressed in kg/sec.

Weight measurement: An electronic weighing balance of sensitivity 0.01g and range of 0.01g to 5000g was utilized in measuring the weight.

Stop watch: This was used to record the time it takes to achieve peeling of the tuber.

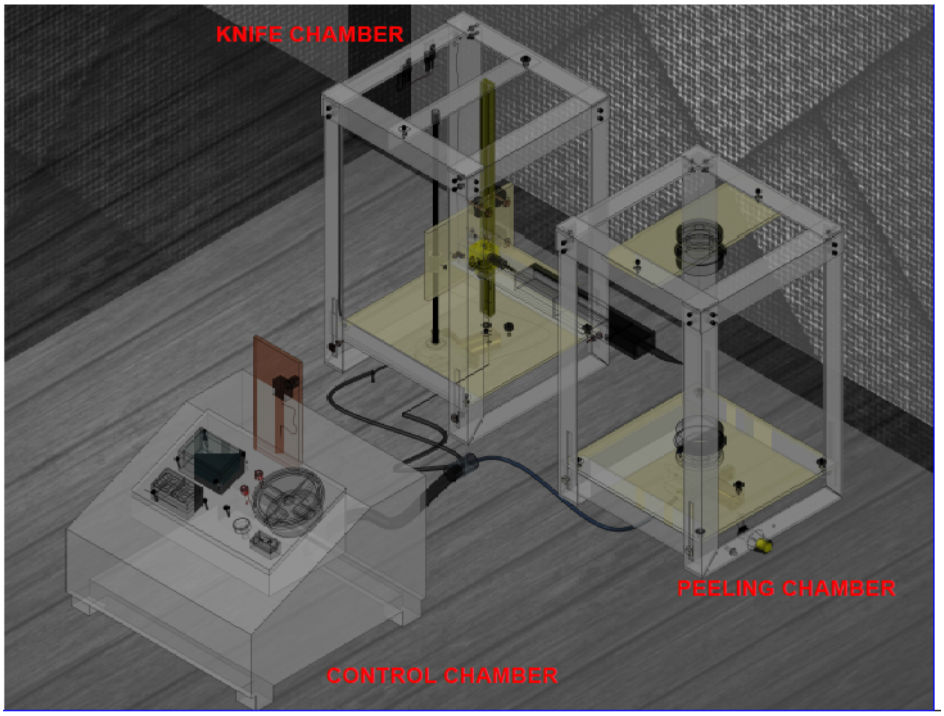

Fig. 1. Empirical arrangement of the peeling mechanism for estimating the throughput capacity

2.5 Input Parameter for Model and Validation

The parameters validation was established by keeping other variables constant, as detailed in Table 3, while changing the size of cassava. Using empirical values and findings from Adetan *et al.* [48], Kolawole *et al.,* [49], Nwagugu and Okonkwo [50], and Aji *et al.,* [51], Table 3 presents the parameter values used to predict the throughput capacity of the peeler.

The predicted throughput capacity expression was established by making a component of the throughput capacity, P (ωm_t) or Q (Ft) to change per period while maintaining others constant and observing the resulting changes in function [52]. This was achieved by plotting the experimental values of T_{Cap} against P = (ωm_t) while keeping Q constant. P = (ωm_t) was estimated by substituting the measured quantities (as listed in Table 3 above) for mass of tuber (m_t), and speed of tuber rotation (ω) into P. Also, T_{Cap} against Q = Ft was plotted keeping P constant while substituting the measured variable. In evaluating the machine throughput capacity for P and Q respectively, the tuber mass and peeling time was changed while other effects were kept constant [52]. The predicted results for machine throughput capacity were plotted against the measured empirical results on a regression curve, utilizing a statistical tool under Microsoft Excel software version 2010. The coefficient of determination (R^2) was calculated to ascertain the model's performance. To evaluate the validity and goodness of fit of the established model for the throughput capacity of selected cassava tubers, the predicted values were related with the empirical results. The obtained R^2 values served as indicators of the model's suitability, demonstrating how effectively it represents the relationship between the predicted and actual throughput capacities.

3. Results

3.1 Model Results

The empirical results of the machine throughput capacity as obtained from the computer vision-assisted peeling process is presented in Table 4 and the predicted machine throughput capacity determined by way of substituting peeling variables values as presented in Table 3 into the machine throughput capacity expression P = (ωm_t) and Q = (Ft) respectively. The table presents a direct relationship that exist between $\left(T_{Cap}\right)$ and the predicted values (P, Q).

The generated result revealed a notable influence of mass of tuber on the throughput capacity required for a cassava peeling mechanism. The plots showing the $\left(T_{Cap}\right)$ against P and Q are presented in Figure 2 and 3 respectively showing their linear expressions and R^2 results indicated in Eq. 14 and 15.

Table 3
Values for predicting the throughput capacity

S/N	Variables	Value
1	Mass of the tuber (g)	677.9 – 835.8
2	Angular speed of tuber (rpm)	3.142 – 4.710
3	Peeling time (s)	116 - 289
4	Peel penetration force(N/mm)	1.21

Table 4
Empirical results $\left(T_{Cap}\right)$ and predicted components (P, Q) of machine throughput capacity of the system

S/N	Mass of tuber (kg)	Peeling Time (s)	$(\boldsymbol{MTC})$	P = $(\boldsymbol{\omega m_t})$	Q = $(\boldsymbol{Ft})$
1	0.786	121	0.00652	3.70206	146.41
2	0.750	143	0.00524	3.53250	173.03
3	0.805	162	0.00497	3.79155	196.02
4	0.798	197	0.00405	3.75858	238.37
5	0.721	236	0.00306	3.39591	285.56

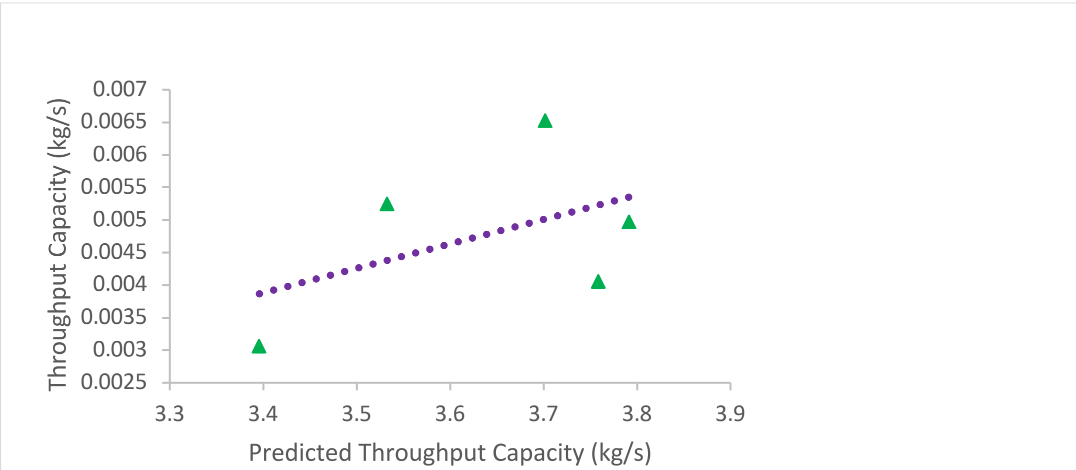

Fig. 2. Variation of throughput capacity against P = (ωm_t) keeping Q constant

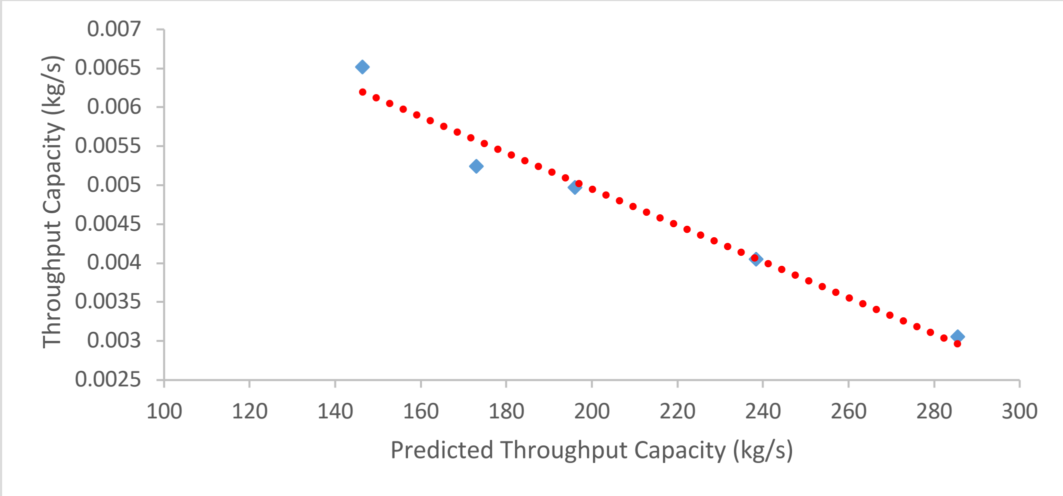

Fig. 3. Variation of throughput capacity against Q = (Ft) keeping P constant

Hence,

$$T_{Cap} = 0.0038P - 0.0089 \qquad R^2 = 0.2333 \tag{14}$$

$$T_{Cap} = -2 \times 10^{-5}Q + 0.096 \qquad R^2 = 0.9654 \tag{15}$$

The graph of P and Q components in Figure 2 and 3 generates a plane surface in linear domain and following the study by Ogunnigbo *et al.* [53], this shows that their combinations favours summation or subtraction. Hence, the component equations generated by the summation and subtraction of Eq. 14 and 15 respectively gives.

$$\therefore\ T_{Cap} = f_1(P, Q) - f_2(P, Q) + J \tag{16}$$

$$\therefore\ T_{Cap} = f_1(P, Q) + f_2(P, Q) + J \tag{17}$$

It is vital to note that;

at f_1, Q was maintained as constant while P varies; and

atf_2, P was equally taken as constant while Q varies

substituting Eq. 14 and 15 into Eq. 16 and performing some algebraic manipulations yields Equation (18)

$$T_{Cap} = 0.0038P + 2 \times 10^{-5}Q - 0.0185 \tag{18}$$

Also substituting the same expressions into Eq. (17) results in;

$$T_{Cap} = 0.0038P - 2 \times 10^{-5}Q - 0.0007 \tag{19}$$

Incorporating the parameters for P and Q into the Equation (18) and (19) above yields;

$$T_{Cap} = 0.0038(\omega m_t) + 2 \times 10^{-5}(Ft) - 0.0185 \tag{20}$$

$$T_{Cap} = 0.0038(\omega m_t) - 2 \times 10^{-5}(Ft) - 0.0007 \tag{21}$$

Introducing additional manipulations based on the concept of Buckingham's π theoretical approach [52] is manipulating with a constant factor. For accurate prediction, a factor of -1 and 1.3 was adopted for Eq. (20) and (21) respectively which generates the predicted model equations presented in Eq. (22) and (23) as given below.

$$T_{Cap} = -0.0038(\omega m_t) - 2 \times 10^{-5}(Ft) + 0.0185 \tag{22}$$

$$T_{Cap} = 0.00494(\omega m_t) - 2.6 \times 10^{-5}(Ft) - 0.00091 \tag{23}$$

Therefore, the final theoretical model expression will either be of the two expressions which yields better statistical inference.

3.2 Model Validation

The predicted framework was validated using results generated from the peeling mechanism, with validation conducted at five different levels of tuber speed and peeling time. A regression analytical approach, implemented through the Microsoft Excel package, was employed to elucidate the theoretical relationships, generate graph, and determine the coefficient of determination (R^2).

Experimental parameter result were incorporated into Eq. (22) and (23) to produce the predicted throughput capacity values. These values were then plotted against the empirical results on a regression curve to calculate the coefficient of determination, as illustrated in Figures 4 and 5, respectively. The relationships defined by Eq. (24) and (25) between the empirical and predicted machine throughput capacity values demonstrated an improved correlation values, with R^2 results of 0.8051 and 0.9047, respectively. To further evaluate the predictive performance of the developed models, error-based statistical indices were computed in addition to the coefficient of determination (R^2). Table 5 presents the RMSE and MAE values for both model formulations. The subtraction-based model (Fig. 5) exhibited lower RMSE and MAE values, indicating reduced prediction error and improved accuracy compared to the addition-based model. This further confirms the suitability of the subtraction-based expression as the final predictive model for throughput capacity.

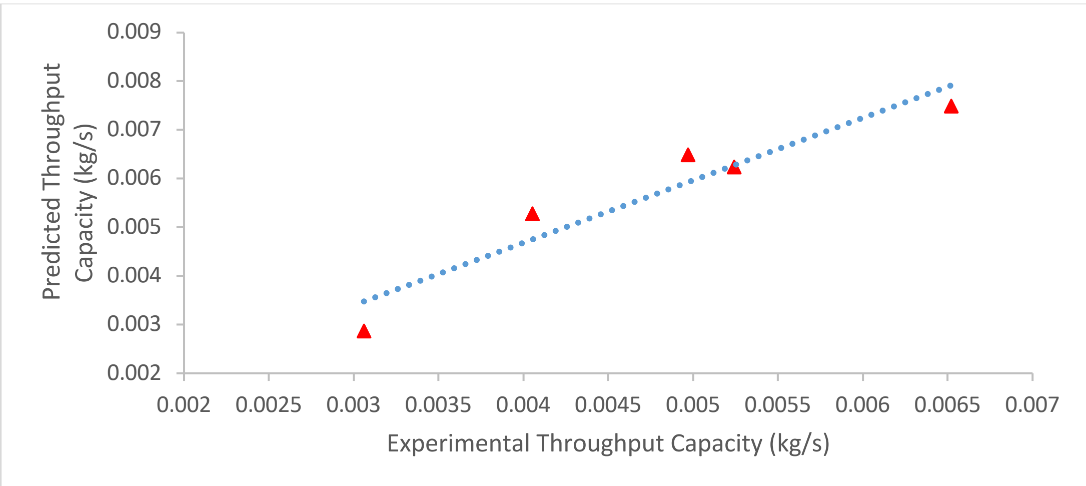

Fig. 4. Graph showing the correlation between empirical and predicted throughput capacity for addition of components parameters

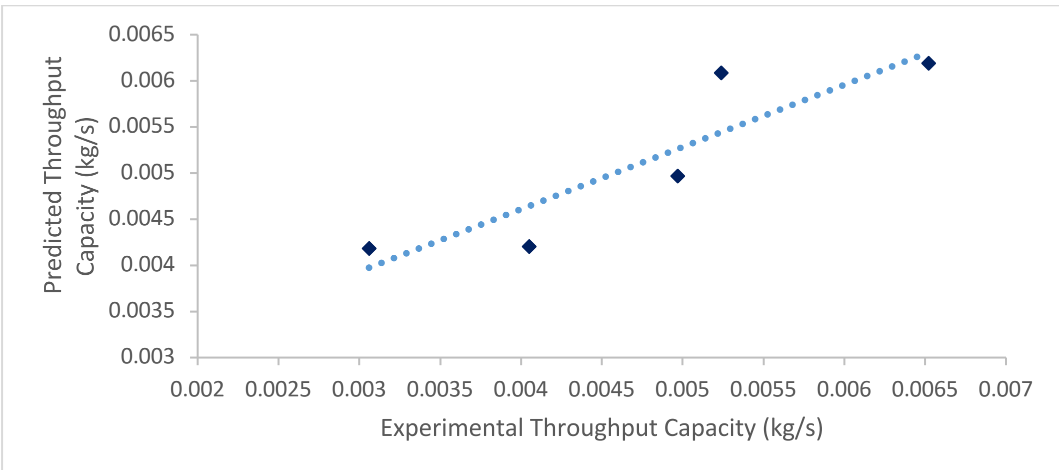

Fig. 5. Graph showing the correlation between empirical and predicted throughput capacity for subtraction of components parameters

$$T_{Cap(pred)} = 0.6741T_{Cap(exp)} + 0.0019 \quad (24)$$
$$T_{Cap(pred)} = 1.283T_{Cap(exp)} - 0.0004 \quad (25)$$

Where,
$T_{Cap(pred)}$ = Predicted throughput capacity and $T_{Cap(exp)}$ is the experimental throughput capacity

Table 5
Statistical validation of the developed throughput capacity models

Model formulation	Coefficient of determination (R^2)	RMSE (kg/s)	MAE (kg/s)
Addition-based model	0.8051	0.00107	0.00098
Subtraction-based model	0.9047	0.00065	0.00049

The high R^2 results obtained for each of the predicted equations indicate that the model development process was robust and effective. This strong correlation suggests that the model is not only reliable for predicting the throughput capacity of cassava but can also be adapted for use with other tubers, such as yam. This versatility reinforces the model's applicability in various agricultural contexts, enabling optimization of peeling processes across different tuber types. The linear validation relationships presented are based on the assumption that the governing dimensionless groups exhibit approximately linear behaviour within the investigated operating range. The models are therefore applicable to the ranges of tuber mass, rotational speed, peel penetration force, and peeling time considered in this study. Deviations between predicted and experimental values may arise from variability in tuber geometry, heterogeneity in peel–flesh adhesion, measurement uncertainties, and simplifying assumptions such as uniform tuber shape and moisture content.

From the established statistical inference, the predictive model equation generated from either the addition or subtraction of components variables yields a higher coefficient of determination (R^2) result of 0.9047.

Hence, the predicted model equation was selected as the expression for the throughput capacity requirement for the peeler and given by the equation below.

$$T_{Cap(pred)} = 1.283T_{Cap(exp)} - 0.0004 \quad (26)$$

4. Conclusions

This study developed and validated a throughput capacity model for a cassava peeling machine using dimensional analysis based on Buckingham's π theorem. The subtraction-based model demonstrated strong agreement with experimental results, yielding a coefficient of determination (R^2 = 0.9047) and low error metrics (RMSE = 0.00065 kg/s and MAE = 0.00049 kg/s), indicating good predictive capability within the investigated operating conditions. The use of a computer vision–assisted peeling mechanism further ensured repeatability and reliability of the experimental validation process. Despite these promising results, the model is subject to certain limitations. Validation was conducted using a limited dataset under controlled laboratory conditions and for specific cassava varieties, tuber sizes, and moisture contents. Assumptions such as uniform tuber geometry, consistent peel–flesh adhesion, and linear relationships between dimensionless groups may contribute to deviations when the model is applied beyond the tested range. Additionally, machine dynamics such as tool wear, vibration effects, and variations in peel thickness were not explicitly incorporated into the current formulation.

Future work should therefore focus on extending model validation across a broader range of cassava varieties, moisture contents, and operational settings, including field-scale applications. Incorporating nonlinear modeling approaches, additional dimensionless parameters, and real-time sensing data may further improve predictive accuracy. Such refinements would enhance the robustness, generalizability, and practical applicability of the proposed throughput model for industrial cassava peeling systems.

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