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| RESEARCH ARTICLE

Design and Performance Evaluation of a Charcoal Briquetting Machine Using Dimensional Analysis and Computational Fluid Dynamics (CFD)

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| ABSTRACT
This study delineates the design and performance assessment of a charcoal briquetting apparatus created through the application of dimensional analysis and Computational Fluid Dynamics (CFD) to augment efficiency, throughput, and energy optimization. A screw-type briquetting apparatus was constructed utilizing a 3 HP motor and achieving an optimized throughput of 41.88 kg/hr, functioning at an efficiency of 79.46%. Buckingham's π theorem was utilized to derive dimensionless models pertinent to essential performance metrics (efficiency, throughput, and energy consumption) predicated on parameters such as pressure, moisture content, feed rate, and die geometry. CFD simulations and SolidWorks-based Finite Element Analysis were employed to substantiate stress, strain, and displacement distributions across the components of the machine. Experimental validation exhibited a strong correlation between predicted and actual values, with coefficients of determination R^2 = 0.7646 for efficiency and R^2 = 0.9532 for throughput, thereby affirming the robustness of the models. The study concludes that the integration of dimensional analysis with parametric simulation markedly enhances the prediction of machine performance. It is recommended that prospective research incorporates environmental impact assessments and cost-benefit analyses for rural-scale deployment, in addition to refining boundary conditions in CFD models for more precise heat transfer predictions.

| KEYWORDS

Charcoal briquetting machine, Dimensional analysis, Buckingham π theorem, Computational Fluid Dynamics (CFD), Performance evaluation, Throughput, Energy consumption, Parametric modeling, Finite Element Analysis (FEA).

| ARTICLE INFORMATION

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1. Introduction

In most African nations, briquetting biomass (especially charcoal) is a relatively recent technique (Mwampamba et al., 2013). However, there are several commercial briquetting systems in Asia, America, and Europe (Njenga, 2013). Briquettes, or high-density biomass fuel, are produced by converting low-density biomass waste (Onukak et al., 2017). The act of gathering flammable materials that are inappropriate because of their low density and compressing them into solid fuel in the proper shape so that it can burn is known as briquetting (Chaney, 2010). Briquettes of charcoal made from agricultural waste are being offered for sale as a substitute for lignite, petroleum coke, and natural coal (Mwampamba et al., 2013). In developed nations, the most common uses of charcoal briquettes are for cooking, heating, barbecue, and camping. Charcoal briquettes are commonly utilised in homes in developing nations. A basic extrusion machine is used as a die to create briquette charcoal, while an effective carboniser turns agricultural waste into charcoal, and an efficient stove is used to burn and cook the charcoal (Okpala et al., 2025). The carboniser is designed to provide a low-oxygen environment for the charcoal briquettes, while the charcoal extruder is designed to produce small-diameter charcoal briquettes (Okpala et al., 2025). The extruder is a screw-type press machine; the mixing time and rpm of the extruder are determined by the person who works on the machine (Bogale, 2009; Somsuk et al., 2008).

Traditional approaches for constructing briquetting machines have mainly been based on empirical methods or trial-and-error procedures, resulting in inadequate performance and inefficiency (Okpala et al., 2025). Engineers may now systematically examine and optimize machine designs using advanced methodologies such as dimensional analysis and Computational Fluid Dynamics (CFD), thanks to developments in computational tools (Onyenanu et al., 2024; Onyenanu et al., 2025). Rapid investigation of design variations and performance simulations is made possible by parametric modelling, a computer technique that entails describing and altering significant system features (Onyenanu et al., 2024). In order to determine the best configurations for briquette density, durability, and combustion efficiency, engineers can utilise parametric modelling in combination with Computational Fluid Dynamics to evaluate important briquette quality factors like compaction pressure, die geometry, feedstock properties, and temperature distribution. This study uses dimensional analysis, specifically the Buckingham π theorem, to develop mathematical models (Onyenanu et al., 2024; Onyenanu et al., 2025) that predict the efficiency of charcoal briquetting devices. The π theorem states that all physically meaningful equations must have dimensional homogeneity to reduce independent variables in complicated settings (Zohuri, 2017). Dimensionless analysis has proven effective in predicting the operational performance of charcoal briquetting equipment.

The theoretical underpinnings of Buckingham's π theorem and its applicability to the design of charcoal briquetting machines will be clarified in this paper. Following a description of the parametric modelling process's technique, the results of experimental studies will be presented (Onyenanu et al., 2025). Therefore, the study's goal is to use computational fluid dynamics and dimensional analysis to build and assess the performance of a charcoal briquetting machine.

2. Literature Review

Table 1: Related works based on design and performance evaluation of a charcoal briquetting machine using dimensional analysis and computational fluid dynamics (CFD)

Author(s) and year of publication	Study Title	Methods used	Key findings
Onyenanu et al., (2025)	"Advancing Coconut Dehusking Technology: A Dimensional Analysis-Based Parametric Model for Local Production"	"Using dimensional analysis based on Buckingham's π theorem"	"The model was validated using experimental study data, showing a maximum correlation coefficient (R^2 = 0.388) between the predicted and measured dehusking efficiencies."
(Mote et al., 2024)	"Manufacturing and performance evaluation of Al/SiC/coconut & bagasse ash composite using novel integrated dimensional analysis (DA) and adaptive neuro fuzzy inference system (ANFIS) techniques"	"Novel integrated dimensional analysis (DA) and adaptive neuro fuzzy inference system (ANFIS) techniques"	"From the experimental findings, it has been observed that the yield strength of the new composition is 161.03 N/mm^2, which is increased by 23.86%. DA-based MRR prediction models show good results with a correlation coefficient (R^2) of 0.9968. "
Ikejiofor & Ndirika, (2022)	"Mathematical model for predicting power requirement of a cocoyam chipper"	Buckingham's Pi Theorem	"The results obtained revealed that the predicted model correlated well with the experimental data, with an R-squared value of 0.998. Also, the difference between the predicted and the measured power requirement means was not statistically significant at the 5 % level."
Ogunnigbo et al., (2022)	"A study on the mathematical model for predicting the peel removal efficiency of a cassava peeler"	"Dimensional analysis based on Buckingham's pi theorem"	"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."
Asonye et al., (2019)	"A mathematical model for predicting the cutting energy of cocoyam (Colocasia Esculenta)"	"Buckingham pi theorem"	"The developed model was validated with experimental data, and a high coefficient of determination of R^2 = 0.982 between the predicted and measured values was established. The obtained predictive model proved appropriate for determining The cutting energy required for cocoyam cormels is up to 98%."
Onyenanu et al., (2024)	Development of a Mathematical Model for Palm Fruit Digester Design: Integrating Dimensional Analysis and Process Optimization "	"Buckingham Pi theorem"	"The results of our analysis indicated that values of 0.9956 for both throughput and machine efficiency were achieved."

As indicated in Table 1, several researchers have applied dimensional analysis and modeling techniques to optimize agricultural and biomass processing equipment. Onyenanu et al. (2025) constructed a parametric model for coconut dehusking using Buckingham's π theorem, reaching a correlation coefficient (R^2 = 0.388). With an R^2 of 0.9968, Mote et al. (2024) increased the yield strength of composite materials by 23.86% by combining dimensional analysis and ANFIS. Ogunnigbo et al. (2022) modelled cassava peeling efficiency with 83.66% reliability, whereas Ikejiofor & Ndirika (2022) projected cocoyam chipping power requirements with great accuracy (R^2 = 0.998). Onyenanu et al. (2024) optimised palm fruit digester performance (R^2 = 0.9956), while Asonye et al. (2019) developed a predictive model for cocoyam cutting energy (R^2 = 0.982). When taken as a whole, these studies show how effective dimensional analysis is at enhancing the sustainability, efficiency, and design of machinery, offering insightful information for improving charcoal briquetting machines.

3. Methodology

3.1 Flow Chart of the Research Pathway

In the course of this work, the following are the patterns in which we undertake to achieve this research;

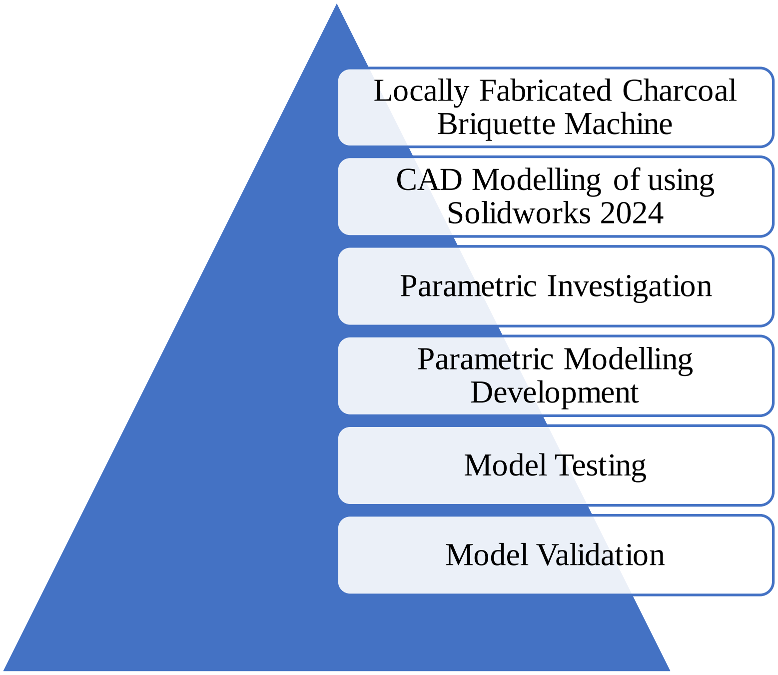


Figure 1: Flow chart of the Model study of charcoal briquetting machine

3.2 Overview of the machine description

The Charcoal Briquetting Machine designed by SEDI-E was a screw press type (conical screw type). Its main parts are the electric motor, pulleys and belts, screw blade shaft, gear control device, twin hopper, control panel, compression chamber, frame, and adjustable briquette die. Power is transmitted through pulleys and belts from the 3.5hp motor to the screw. After starting the motor, the raw material was fed into a screw that compressed and extruded it through the die. Design considerations were based on forces required to drive the shaft, the diameter of the screw blade shaft, the dynamic load on the bearing transmitted by the screw shaft, and the power required to compact pulverized feedstock as well as extrude the resultant briquette from the die. Figure 2 shows the CAD model and the locally fabricated charcoal briquetting machine.

Table 2: Technical Specification Table for the charcoal briquette machine:

Parameter	Specification
Machine Type	Charcoal Briquette Machine
Model	Custom-designed (Based on CAD SolidWorks 2023)
Power Source	Electric Motor
Motor Power	3 HP (2.2 kW)
Voltage Requirement	220V/380V (Depending on configuration)
Machine Capacity	40-50 kg/hr (Based on optimization results)
Efficiency	79.46%
Throughput	41.88 kg/hr
Briquette Size	50mm diameter, 100mm length
Compression Force	1500 N
Operating Speed	79.46 RPM (Optimized using RSM in Design-Expert 13)
Material of Construction	Mild Steel & Stainless-Steel Components
Heating Mechanism	Screw Press with Internal Heating Element
Binding Agent Required	None (Uses high-pressure compaction)
Control System	Manual/Automated (Depending on configuration)
Finite Element Analysis	Stress, strain, displacement, and safety factor analysis using SolidWorks Simulation
Dimensional Analysis	Conducted using Buckingham Pi Theorem
Optimization Methodology	Response Surface Methodology (RSM)
Validation Method	Experimental Testing and Statistical Analysis

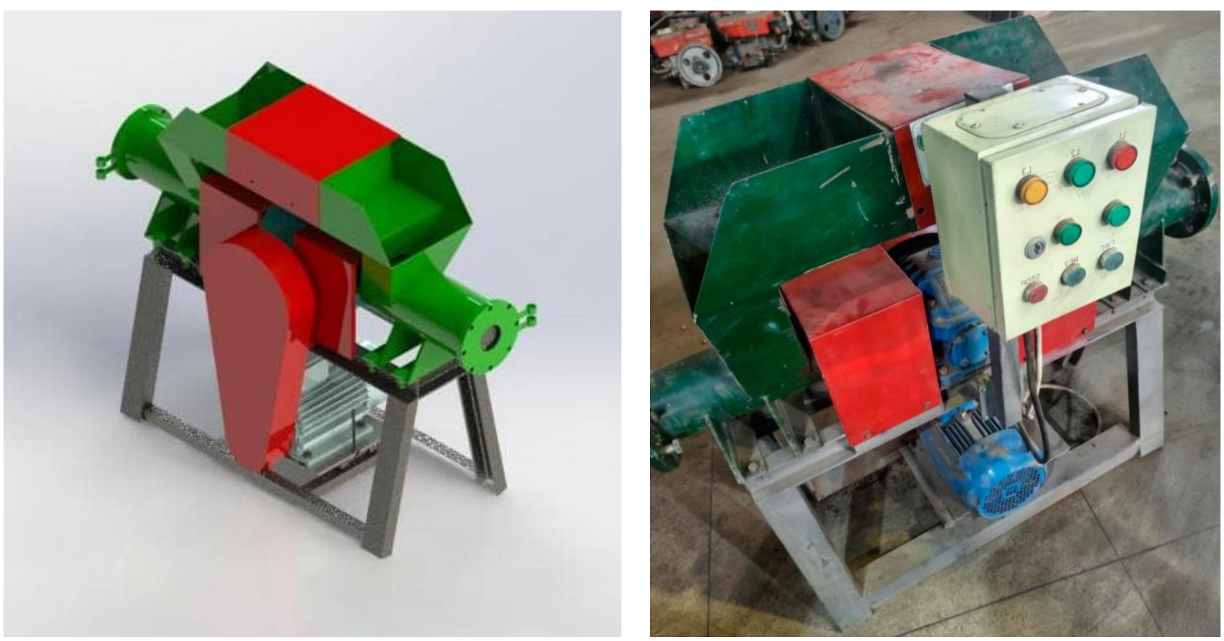


Figure 2: CAD model and the locally fabricated charcoal briquetting machine

3.3 Working Operation

The screw-type charcoal briquetting machine operates through a continuous extrusion process to transform charcoal powder or coal dust into high-density briquettes. The process begins with material feed, where raw charcoal particles are loaded into the machine's hopper. A rotating screw conveyor then transports the material into the compression chamber, where it undergoes intense pressure as the screw forces it through a tapered die. During compression, a binding agent is injected into the mixture to enhance structural integrity, while simultaneously applied heat activates the binder's adhesive properties. As the screw continues its advancement, the compressed material takes shape within the die, forming consistent cylindrical briquettes. Upon reaching the desired compaction, a cutting mechanism trims the extruded material to specified lengths before ejecting the finished briquette. The screw then retracts to its initial position, allowing the cycle to repeat continuously. This screw extrusion principle ensures production of uniform briquettes with optimal density (typically 1.1-1.4 g/cm^3) and mechanical strength, making them suitable for both domestic and industrial applications. The entire process combines mechanical compression, thermal activation, and precision shaping to convert waste charcoal fines into value-added fuel products.

3.4 Parametric Modelling Using Buckingham's Pi Theory

3.4.1 Model Development

a) Efficiency Model

The efficiency of the charcoal briquette machine "η" made by SEDI-E depends on the compression pressure (P), particle size (d), moisture content of raw material (%m), binder concentration (B_c), viscosity (μ), and raw material feed rate (F_r). Therefore, the efficiency "η" in terms of dimensionless parameters, is expressed as:

Table 3. Variables affecting the efficiency of the charcoal briquette machine

S/N	Variables	Symbol	Unit	Dimension
1	Compression pressure	P	Pa	$ML^{-1}T^{-2}$
2	particle size	d	mm	L
3	Viscosity	μ	$N.s/m^2$	$ML^{-1}T^{-1}$
4	Efficiency	η	%	$M^0L^0T^0$
5	Moisture content	m_c	%	L^0T^0
6	Binder concentration	Bc	Kg/m^3	ML^{-3}
7	Feed rate	Fr	mm^2/sec	L^2T^{-1}

η is a function of P, d, μ, m_c, B_c, Fr

$\eta = f(P, d, \mu, m_c, B_c, Fr)$ (3.1)

Note that ***dependent variables = independent variables***

However, the functional relationship between the dependent and independent variables can be written as:

$f = (P, d, \mu, m_c, B_c, Fr, \eta) = 0$ (3.2)

The total number of variables, n, is equal to 7

Number of fundamental dimensions for the problems = 3 (M, L, T).

Therefore, the number of π-term (ie. π_1, π_2, π_3, π......n)

n - m = 7 – 3 = 4

However, there will be for π_1, π_2, π_3, and π_4,

$\pi_1 = C_e f(\pi_2\ \pi_3\ \pi_4)$ (3.3)

where; $\mathbf{C_e}$ = Efficiency constant, $\pi_1, \pi_2, \pi_3, \pi_4$, = Pi terms to be determined.

$\pi_1 = D^{a1}\ P^{b1}\ \mu^{c1}\ (\eta)$ (3.4)

$\pi_2 = D^{a2}\ P^{b2}\ \mu^{c2}\ (F_r)$ (3.5)

$\pi_3 = D^{a3}\ P^{b3}\ \mu^{c3}\ (M_c)$ (3.6)

$\pi_4 = D^{a4}\ P^{b4}\ \mu^{c4}\ (B_c)$ (3.7)

Considering eqn 3.4, $\pi_1 = D^{a1}\ P^{b1}\ \mu^{c1}\ (\eta)$

Substitute dimensions on both sides

$M^0L^0T^0 = L^{a1}\ (M^1 L^1 T^{-2})^{b1}\ (M^1 L^{-1} T^{-1})^{c1}\ M^0L^0T^0$

$M^0L^0T^0 = M^{b1 + c1} \quad L^{a1 + b1 - c1} \quad T^{-2b1 - c1}$
Comparing the powers of M L T
Powers of M = $b_1 + c_1 = 0$
$c_1 = -b_1.$ Where, $b_1 = 0$ (from T-value)
Therefore, $c_1 = 0$
Power of L = $a_1 + b_1 - c_1 = 0$ (from the power of M, $c_1 = -b_1$)
$a_1 + b_1 - (-b_1) = 0$
$a_1 + 2b_1 = 0$
$a_1 = -2b_1$ Where, $b_1 = 0$ (from T-value)
$a_1 = 0$
Power of T = $-2b_1 - c_1 = 0$
$-2b_1 - (-b_1) = 0$ (from the power of M, $c_1 = -b_1$)
$-2b_1 + b_1 = 0$
$b_1 = 0$
substituting the power of the values a, b, c, in the 1st pi term 3.4,
$\pi_1 = D^0 \quad P^0 \quad \mu^0 \quad (\eta)$
$\pi_1 = (\eta)$ (3.8)
from Eqn 3.5,
$\pi_2 = D^{a2} \quad P^{b2} \quad \mu^{c2} \quad (F_r)$
Substitute dimensions on both sides
$M^0L^0T^0 = L^{a2} \quad (M^1 L^1 T^{-2})^{b2} \quad (M^1 L^{-1} T^{-1})^{c2} \quad L^2T^{-1}$
$L^2T^{-1} = M^{b2 + c2} \quad L^{a2 + b2 - c2 + 2} \quad T^{-2b2 - c2 - 1}$
Comparing the powers of M L T
Powers of M = $b_2 + c_2 = 0$
$C_2 = -b_2.$ Where, $b_2 = -1$ (from T-value)
Therefore, $c_2 = 1$
Power of L = $a_2 + b_2 - c_2 + 2 = 0$ (from the power of M, $c_2 = -b_2$)
$a_2 + b_2 - (-b_2) + 2 = 0$
$a_2 + 2b_2 + 2 = 0$
$a_2 = -2b_2 - 2$ Where, $b_2 = -1$ (from T-value)
$a_2 = 0$
Power of T = $-2b_2 - c_2 - 1 = 0$
$-2b_2 - (-b_2) - 1 = 0$ (from the power of M, $c_2 = -b_2$)
$-2b_2 + b_2 - 1 = 0$
$b_2 = -1$
substituting the power of the values a, b, c, in the 2nd pi term 3.5,
$\pi_2 = D^0 \quad P^{-1} \quad \mu^1 \quad (F_r)$
$\pi_2 = \frac{\mu . F_r}{P}$ (3.9)
Considering eqn 3.6,
$\pi_3 = D^{a3} \quad P^{b3} \quad \mu^{c3} \quad (M_c)$
Substitute dimensions on both sides
$M^0L^0T^0 = L^{a3} \quad (M^1 L^1 T^{-2})^{b3} \quad (M^1 L^{-1} T^{-1})^{c3} \quad L^0T^0$
$L^0T^0 = M^{b3 + c3} \quad L^{a3 + b3 - c3} \quad T^{-2b3 - c3}$
Comparing the powers of M L T
Powers of M = $b_3 + c_3 = 0$
$C_3 = -b_3.$ Where, $b_3 = 0$ (from T-value)
Therefore, $c_3 = 0$
Power of L = $a_3 + b_3 - c_3 = 0$ (from the power of M, $c_3 = -b_3$)
$a_3 + b_3 - (-b_3) = 0$
$a_3 + 2b_3 = 0$
$a_3 = -2b_3$ Where, $b_3 = 0$ (from T-value)

$a_3 = 0$
Power of T = $-2b_3 - c_3 = 0$
$-2b_3 - (-b_3) = 0$ (from the power of M, $c_3 = -b_3$)
$-2b_3 + b_3 = 0$
$b_1 = 0$
substituting the power of the values a, b, c, in the 3rd pi term 3.6,
$\pi_3 = D^0 \quad P^0 \quad \mu^0 \quad (M_c)$
$\pi_3 = (M_c)$ (3.10)
Considering eqn 3.7
$\pi_4 = D^{a4} \quad P^{b4} \quad \mu^{c4} \quad (B_c)$ (3.11)
Substitute dimensions on both sides
$M^0L^0T^0 = L^{a4} \quad (M^1 L^1 T^{-2})^{b4} \quad (M^1 L^{-1} T^{-1})^{c4} \quad ML^{-3}$
$M^1L^{-3} = M^{b4 + c4 + 1} \quad L^{a4 + b4 - c4 - 3} \quad T^{-2b4 - c4}$
Comparing the powers of M L T
Powers of M = $b_4 + c_4 + 1 = 0$
$C_4 = -b_4 - 1$ Where, $b_4 = 0$ (from T-value)
Therefore, $c_4 = -1$
Power of L = $a_4 + b_4 - c_4 - 3 = 0$ (from the power of M, $c_4 = -b_4$)
$a_4 + b_4 - (-b_4) - 3 = 0$
$a_4 + 2b_4 - 3 = 0$
$a_4 = -2b_4 - 3$ Where, $b_4 = 0$ (from T-value)
$a_4 = -3$
Power of T = $-2b_4 - c_4 = 0$
$-2b_2 - (-b_4) = 0$ (from the power of M, $c_4 = -b_4$)
$-2b_4 + b_4 = 0$
$b_4 = 0$
substituting the power of the values a, b, c, in the 4th pi term 3.7,
$\pi_4 = D^{-3} \quad P^0 \quad \mu^{-1} \quad (B_c)$
$\pi_4 = \frac{B_c}{D^3\mu}$ (3.11)
Substituting the values of π_1, π_2, π_3, and π_4 in equation one
$f = (\eta, \frac{\mu.F_r}{P}, (M_c), \frac{B_c}{D^3\mu})$ (3.12)
$\eta = \Phi\,(\frac{\mu.F_r}{P}, (M_c), \frac{B_c}{D^3\mu})$ (3.13)
To determine the η-model, substitute the **π** values above into equation 3.3. However, the efficiency model can be expressed as:

$$\boldsymbol{\eta = C_e\left(\frac{m_c B_c F_r}{PD^3}\right)}$$

b) Thorough Put Model

The thorough put of the charcoal briquette machine "T_h" depends on the screw feed speed, die rotation speed, raw material bulk density ρ, number of die holes N, roller pressure, feeder capacity, and machine uptime U. Therefore, the thorough put of the charcoal briquetting machine "T_h" in terms of dimensionless parameters is expressed as:

Table 4: Variables affecting the thorough put of the charcoal briquetting machine

S/N	Variables	Symbol	Unit	Dimension
1	Screw feed speed	S	m/s	LT^{-1}
2	Die rotation speed	D	rpm	T^{-1}
3	Material bulk density	ρ	Kg/m^3	ML^{-3}
4	Thorough put	Th	Kg/hr	$M\ T^{-1}$
5	Number of die hole	N	-	-
6	Roller pressure	P	Pa	$ML^{-1}T^{-2}$
7	Feeder capacity	F	Kg/hr	MT^{-1}
8	Machine uptime	U	hr	T

$T_h = f$ (S, D, ρ, N, P, F, U). (3.15)
f (T_h, S, D, ρ, N, P, F, U) = 0 (3.16)
The total number of variables, n is equal to 8
Number of fundamental dimensions = 3(MLT)
Therefore, the number of π-term = n-m=5
However, there will be for $\pi_{11}, \pi_{22}, \pi_{33,}\pi_{44,}\pi_{55}$
Hence eqn. 3.47 can be written as $f(\pi_{11}, \pi_{22}, \pi_{33,}\pi_{44,}\pi_{55})$ = 0 (3.16)
Choosing S, D, ρ as repeating variables, we get π-terms as
$\pi_1 = S^a, D^b, \rho^c, T_h$ (3.17)
$\pi_2 = S^a, D^b, \rho^c, N$ (3.18)
$\pi_3 = S^a, D^b, \rho^c, P$ (3.19)
$\pi_4 = S^a, D^b, \rho^c, F$ (3.20)
$\pi_5 = S^a, D^b, \rho^c, U$ (3.21)

Table 5: Dimensional matrix of variables for thorough put model

	Variables							
Dimensional Unit	**S**	**D**	**ρ**	**T_h**	**N**	**P**	**F**	**U**
	a	b	c	D	e	f	g	h
M	0	0	1	1	0	1	1	0
L	1	0	-3	0	0	-1	0	0
T	-	-1	0	-1	0	-2	-1	1

First π-term
$\pi_1 = S^a, D^b, \rho^c, T_h$
Writing dimensions on both sides, we have:
$[MLT]^0 = [LT^{-1}]^a\ [T^{-1}]^b\ [ML^{-3}]^c\ [MT^{-1}]$ (3.22)

Equating powers of M, L, and T on both sides
M: 0 = c + 1, c = -1 (3.23)
L: 0 = a – 3c, a = 3c, = 3(-1), a = -3 (3.24)
T: 0 = -a –b -1, -(-3) -1 = b, b = 2 (3.25)
Substituting the values of a, b, and c into eqn. 3.49 above $\pi_1 = S^{-3}, D^2, \rho^{-1}, T_h$

$$\pi_1 = \frac{T_h D^2}{\rho S^3} \quad (3.26)$$

Second π-term
$\pi_1 = S^a, D^b, \rho^c, N$
Writing dimensions on both sides, we have:

$[MLT]^0 = [LT^{-1}]^a\ [T^{-1}]^b\ [ML^{-3}]^c$ (3.27)

N is dimensionless

Equating powers of M, L, and T on both sides

M: 0 = c, c = 0 (3.28)

L: 0 = a – 3c, a = 3c, = 3(0), a = 0 (3.29)

T: 0 = -a –b, - (0) -b = 0, b = 0 (3.30)

Substituting the values of a, b, and c into eqn. 3.50 above

$\pi_2 = S^0\ D^0\ \rho^0\ N$ (3.31)

π_2 = N (3.32)

Third π-term

$\pi_3 = S^a, D^b, \rho^c, P$

Writing dimensions on both sides, we have:

$[MLT]^0 = [LT^{-1}]^a\ [T^{-1}]^b\ [ML^{-3}]^c\ [ML^{-1}T^{-2}]$ (3.33)

Equating powers of M, L, and T on both sides

M: 0 = c + 1, c = -1 (3.34)

L: 0 = a – 3c - 1, a = 3c + 1, = 3(-1) + 1, a = -2 (3.35)

T: 0 = -a –b -2, -(-2) -2 = b, b = 0 (3.36)

Substituting the values of a, b, and c into eqn. 3.51 $\pi_3 = S^{-2}, D^0, \rho^{-1}, P$ (3.37)

$\pi_3 = \frac{P}{\rho S^2}$ (3.38)

Fourth π-term

$\pi_4 = S^a, D^b, \rho^c, F$

Writing dimensions on both sides, we have:

$[MLT]^0 = [LT^{-1}]^a\ [T^{-1}]^b\ [ML^{-3}]^c\ [MT^{-1}]$ (3.39)

Equating powers of M, L, and T on both sides

M: 0 = c + 1, c = -1 (3.40)

L: 0 = a – 3c, a = 3c, = 3(-1), a = -3 (3.41)

T: 0 = -a –b -1, -(-3) -1 = b, b = 2 (3.42)

Substituting the values of a, b, and c into eqn. 3.52 $\pi_3 = S^{-3}, D^2, \rho^{-1}, F$ (3.43)

$\pi_4 = \frac{FD^2}{\rho S^3}$ (3.44)

Fifth π-term

$\pi_4 = S^a, D^b, \rho^c, U$

Writing dimensions on both sides, we have:

$[MLT]^0 = [LT^{-1}]^a\ [T^{-1}]^b\ [ML^{-3}]^c\ [T]$ (3.45)

Equating powers of M, L, and T on both sides

M: 0 = c, c = 0 (3.46)

L: 0 = a – 3c, a = 3c, = 3(0), a = 0 (3.47)

T: 0 = -a –b +1, 0 +1 = b, b = 1 (3.48)

Substituting the values of a, b, and c into eqn. 3.52 $\pi_5 = S^0, D, \rho^0, U$ (3.49)

$\pi_5 = DU$ (3.50)

Summary of the π-terms

$\pi_1 = \frac{T_h D^2}{\rho S^3}$

π_2 = N

$\pi_3 = \frac{P}{\rho S^2}$

$\pi_4 = \frac{FD^2}{\rho S^3}$

$\pi_5 = DU$

To determine the T_h-model, substitute the **π** values above into equation 3.48. However, the thorough put model can be expressed as:

$f\,[\frac{T_h D^2}{\rho S^3}, N, \frac{P}{\rho S^2}, \frac{FD^2}{\rho S^3}, DU]$

$\frac{T_h D^2}{\rho S^3} = C_T[N, \frac{P}{\rho S^2}, \frac{FD^2}{\rho S^3}, DU]$ (3.51)

Where C_T is the thorough put constant.

$\frac{T_h D^2}{\rho S^3} = C_T[N.\frac{P}{\rho S^2}.\frac{FD^2}{\rho S^3}.DU]$ (3.52)

$T_h = C_T[N.\frac{P}{\rho S^2}.\frac{FD^2}{\rho S^3}.DU]\ \frac{S^3}{D^2}$ (3.53)

$T_h = C_T[\frac{NPFDU}{S^2\rho^2}]$

c) Energy Consumption Model

The energy consumption model of the charcoal briquette machine "Ec" depends on moisture content (M_c) screw feed speed (V), compression pressure (P), briquette density (ρ), friction (F_r), die size and shape, temperature, and machine efficiency. Therefore, the energy consumption of the charcoal briquetting machine "Ec" in terms of dimensionless parameters is expressed as:

Table 6: Variables affecting the energy consumption of the charcoal briquetting machine

S/N	Variables	Symbol	Unit	Dimension
1	Screw feed speed	v	m/s	L^1T^{-1}
2	Moisture content	M_c	%	L^0T^0
3	Briquette density	ρ	Kg/m^3	M^1L^{-3}
4	Energy consumption	E_c	Kwh/ton	L^2T^{-2}
5	Compression pressure	P	Pa	$ML^{-1}T^{-2}$
6	Friction	F_r	N	$M^1L^1T^{-2}$
7	Die size and shape	D_s	m	L
8	Temperature	T	K	ϴ
9	Efficiency	η	%	$M^0L^0T^0$

$E_c = f(M_c, V, D, \rho, T, P, F_r, \eta)$. (3.55)

$f(E_c, M_c, V, D, \rho, T, P, F_r, \eta) = 0$ (3.56)

The total number of variables, n is equal to 9

Number of fundamental dimensions = 4 (MLTϴ)

Therefore, the number of π-term = n-m= 9 – 4 = 5

However, there will be for $\pi_1, \pi_2, \pi_3, \pi_4, \pi_5$

$\pi_1 = D^a\ V^b\ \ \rho^c\ \ T^d\ \ E_c$ (3.57)

$M^0L^0T^0\Theta^0 = L^a\ \ (L^1T^{-1})^b\ \ (M^1L^{-3})^c\ L^2T^{-2}$

$L^2T^{-2}\ \Theta^0 = M^c\ \ L^{a+b-3c+2}\ \ T^{-b-2}$

The power of m; c = 0

The power of L; a + b – 3c + 2 = 0 but c = 0

a + b + 2 = 0;

a = -b -2 but b = -2

a = 0

The power of T; -b – 2 = 0,

b = -2

substitute the value of the pi-term a, b, c in equation 3.57

$\pi_1 = D^0 \quad V^{-2} \quad \rho^0 \quad T^0 \quad E_c$

$\pi_1 = \frac{E_c}{V^2}$ (3.58)

$\pi_2 = D^a \quad V^b \quad \rho^c \quad T^d \quad M_c$ (3.59)

$M^0L^0T^0\Theta^0 = L^a \quad (L^1T^{-1})^b \quad (M^1L^{-3})^c \; L^0T^0$

$L^0T^0\Theta^0 = M^c \quad L^{a+b-3c} \quad T^{-b}$

The power of M; c = 0

The power of L; a + b – 3c = 0 but c = 0

a + b = 0;

a = -b but b = 0

a = 0

The power of T; -b = 0,

b = 0

substitute the value of the pi-term a, b, c in equation 3.59

$\pi_2 = D^0 \quad V^0 \quad \rho^0 \quad T^0 \quad M_c$

$\pi_2 = M_c$ (3.60)

$\pi_3 = D^a \quad V^b \quad \rho^c \quad T^d \quad P$ (3.61)

$M^0L^0T^0\Theta^0 = L^a \quad (L^1T^{-1})^b \quad (M^1L^{-3})^c \; M^1L^{-1}T^{-2}$

$ML^{-1}T^{-2}\,\Theta^0 = M^{c+1} \quad L^{a+b-3c-1} \quad T^{-b-2}$

The power of M; c +1 = 0, c = -1

The power of L; a + b – 3c – 1 = 0, a + b + 2 = 0 but c = -1

a = -b – 2 but b = -2

a = 0

The power of T; -b – 2 = 0, b = -2

substitute the value of the pi-term a, b, c in equation 3.61

$\pi_3 = D^0 \quad V^{-2} \quad \rho^{-1} \quad T^0 \quad P$

$\pi_3 = \frac{P}{V^2 P}$ (3.62)

$\pi_4 = D^a \quad V^b \quad \rho^c \quad T^d \quad F_r$ (3.63)

$M^0L^0T^0\Theta^0 = L^a \quad (L^1T^{-1})^b \quad (M^1L^{-3})^c \; M^1L^1T^{-2}$

$M^1L^1T^{-2}\Theta^0 = M^{c+1} \quad L^{a+b-3c+1} \quad T^{-b-2}$

The power of M; c +1 = 0, c = -1

The power of L; a + b – 3c + 1 = 0, a + b + 4 = 0 but c = -1

a = -b – 4 but b = -2

a = -2

The power of T; -b – 2 = 0, b = -2

substitute the value of the pi-term a, b, c in equation 3.63

$\pi_4 = D^{-2} \quad V^{-2} \quad \rho^{-1} \quad T^0 \quad F_r$

$\pi_4 = \frac{F_r}{D^2V^2\rho}$ (3.64)

$\pi_5 = D^a \quad V^b \quad \rho^c \quad T^d \quad (\eta)$ (3.65)

Substitute dimensions on both sides

$M^0L^0T^0\Theta^0 = L^a \quad (L^1T^{-1})^b \quad (M^1L^{-3})^c \; M^0L^0T^0$

$M^0L^0T^0\Theta^0 = M^c \quad L^{a+b-3c} \quad T^{-b}$

Comparing the powers of M L T Θ

Powers of M; c = 0

Power of L = a + b – 3c = 0 but c = 0

a = b Where, b = 0 (from T-value)

a = 0

Power of T = b = 0

substituting the power of the values a, b, c, in equation 3.65

π_5 = D^0 V^0 ρ^0 T^0 (η)

π_5 = (η) (3.66)

Summary of the π-terms

$\pi_1 = \frac{E_c}{V^2}$

$\pi_2 = M_c$

$\pi_3 = \frac{P}{V^2 P}$

$\pi_4 = \frac{F_r}{D^2 V^2 \rho}$

$\pi_5 = \eta$

The energy consumption model

$$E_c = \frac{M_c P F_r}{D^2 V^2 \rho^2}$$

3.4.2 Value of the Constant

a) Determination of the Efficiency Constant

The determination of the efficiency constant involved the utilization of linearized expressions for π_4 and π_1 namely, [$\frac{B_c}{D^3 \mu}$ and η] extracted from the developed model. This process was executed employing the method of least squares, a statistical technique, as elaborated by the works of [Bolaji, 2008] and [Ikejiofor, 2016]. The efficiency constant, which was determined to be 0.0023x, was thus obtained from the gradient of the line that best matches the data. But as Figure 3 illustrates, the regression coefficient R^2 that was found was 0.0023.

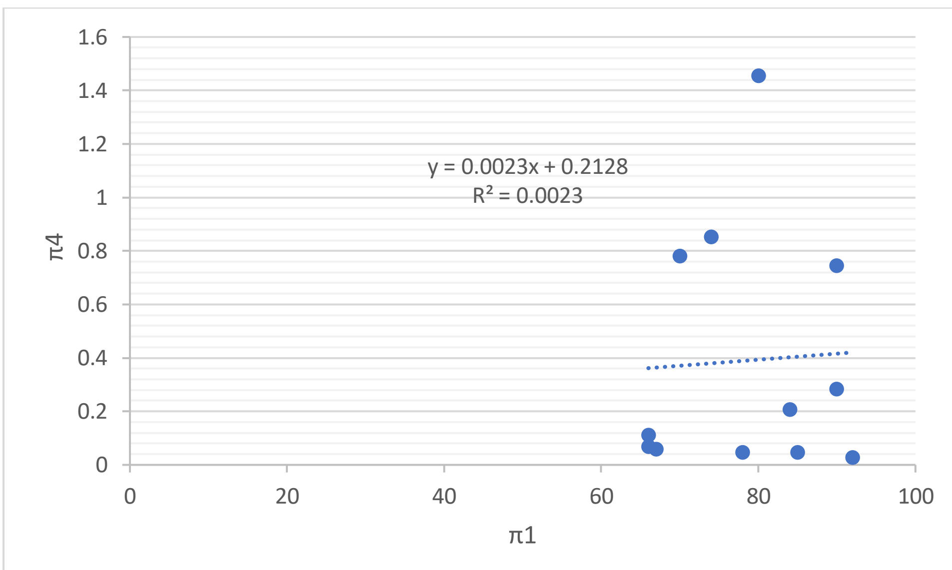


Figure 3: Determination of the Efficiency Constant

b) Determination of Throughput constant

Determining the throughput constant involved using simplified equations for π_4 and π_1, specifically [DU and $\frac{T_h D^2}{\rho S^3}$]. These equations were derived from a complex model we created. We used a reliable statistical technique called the method of least squares, supported by the research of [Bolaji, 2008] and [Ikejiofor, 2016]. As Figure 4 illustrates, the regression coefficient R^2 that was found was 0.2843.

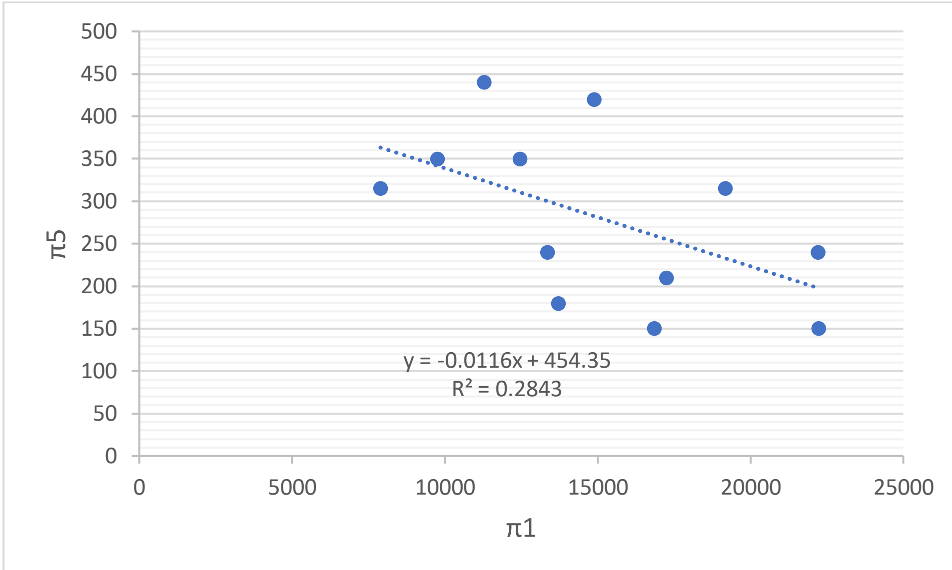


Figure 4: Determination of Throughput constant

c) Determination of Energy Consumption Constant

The determination of the energy consumption constant involved the utilization of linearized expressions for π_5 and π_1 namely, [η and $\frac{E_c}{V^2}$] extracted from the developed model. Nonetheless, as demonstrated in Figure 5, the derived regression coefficient R^2 was calculated to be 0.0568.

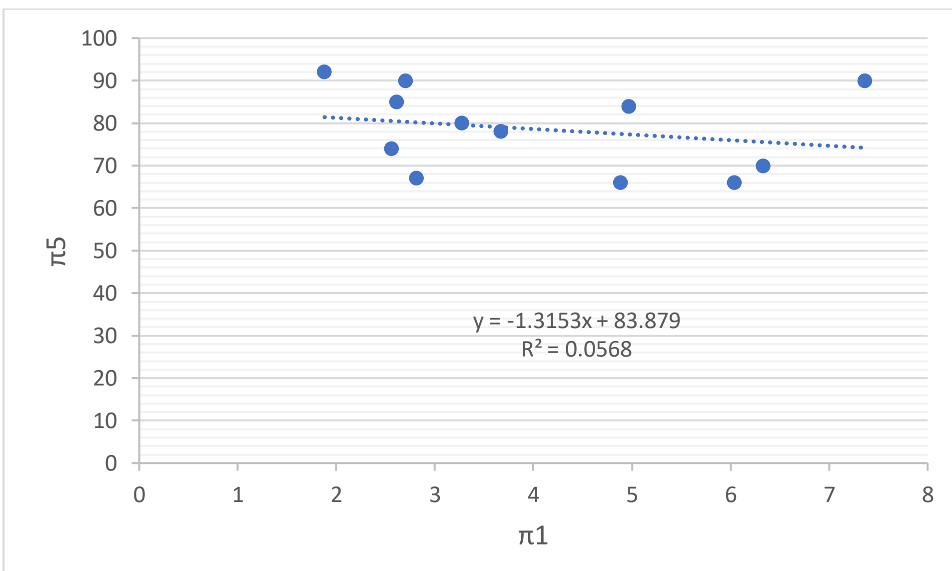


Figure 5: Determination of Energy Consumption Constant

3.4.3 Model Validation

a) Efficiency

In Table 6, both calculated and measured throughput are displayed (Onyenanu et al., 20223). Measured efficiency values were determined using Equation 3.40. The analysis demonstrated a positive linear relation between the model and the data obtained from the existing briquette machine as represented by the equation y = 0.58x + 42.556. The coefficient of determination, R^2 = 0.7646, shows the model's predictive accuracy. This entails that approximately 76.46% of the variance in the predicted values based on the calculated values. This high correlation suggests that the efficiency model is reliable for predicting outcomes.

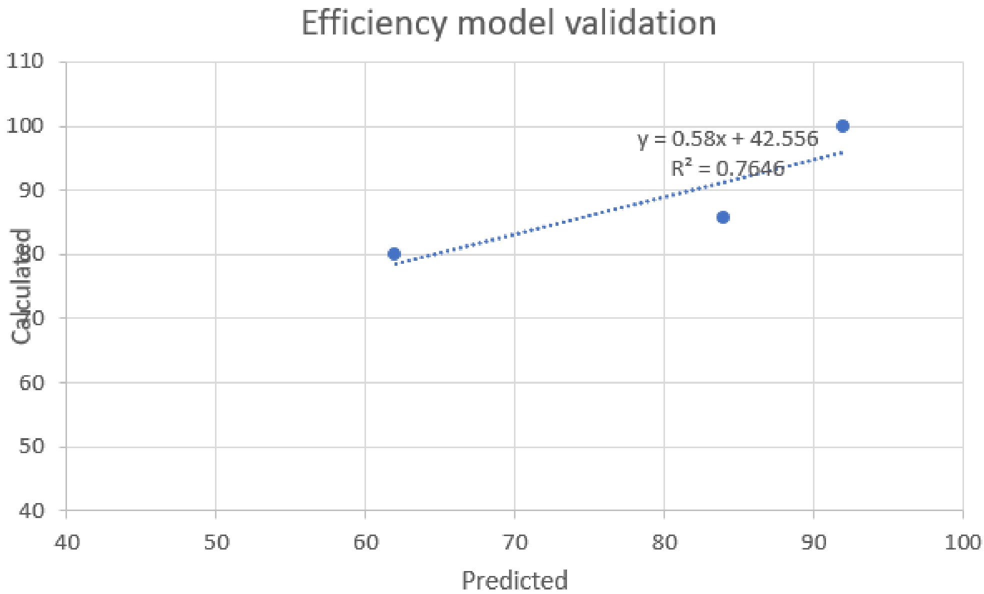


Figure 6: Measured efficiency versus computed efficiency

b) Throughput

From Figure 7, the plot demonstrated a favourable alignment between the model and the data obtained from the existing briquette machine represented by the equation y = 2.1448x—314.27. The high coefficient of determination, R^2 = 0.9532, depicts a robust correlation, showing the model's excellent predictive performance. however, it implies that the computed values are highly reliable in estimating the calculated values for the throughput model.

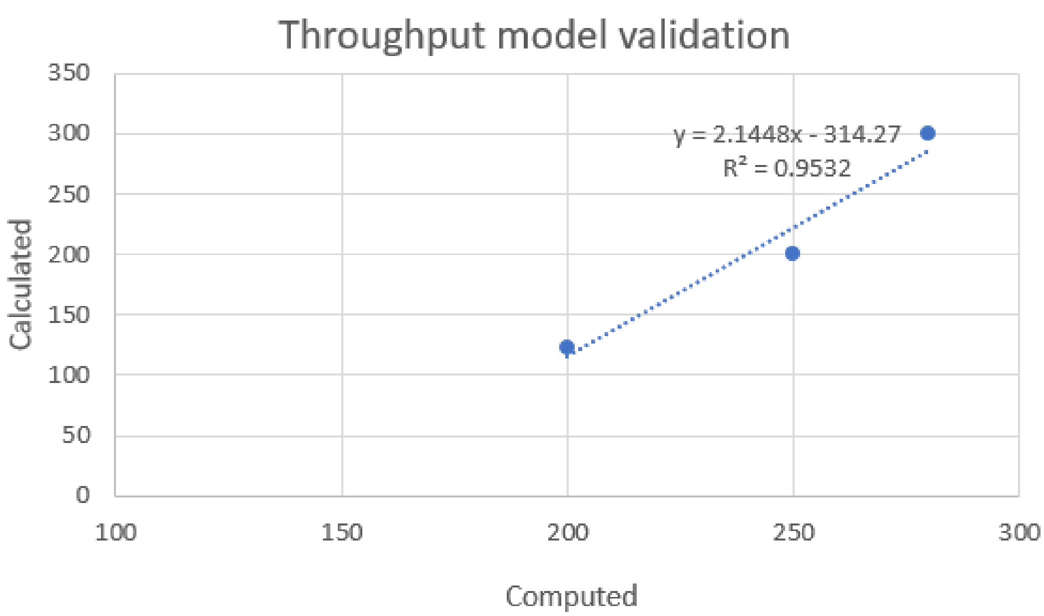
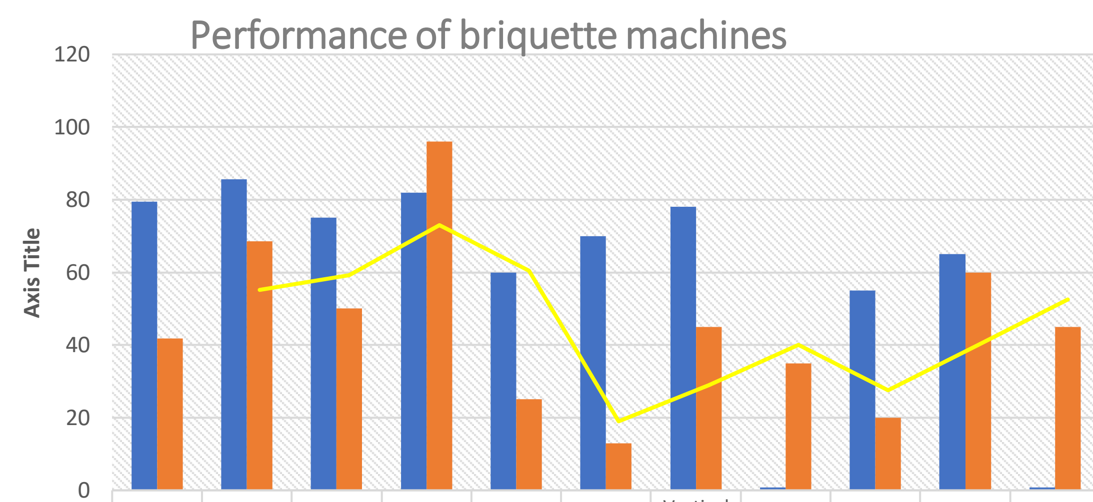


Figure 7: Measured throughput versus computed throughput

3.4.4 Comparative analysis for the validation

The comparative analysis for the validation ensures the reliability of the briquette machine performance predictions by comparing simulated outcomes with experimental or literature-based results. Figure 8 presents efficiency (%) and throughput (kg/hr) values for various briquette machines, including our optimal sample (79.46% efficiency, 41.88 kg/hr throughput), benchmarked against established studies. For instance, the piston-type briquetting machine (85.70%, 68.56 kg/hr) from Adebayo et al. (2024) and the hydraulic piston press (82.00%, 96.00 kg/hr) from

Orisaleye et al. (2018) provide high-performance references, while lower-end systems like the manual briquetting machine (60.00%, 25.00 kg/hr) from Romallosa & Kraft (2017) highlight variability. Our optimal sample aligns closely with mid-to-high-tier machines, such as the vertical ring die (78.00%, 45.00 kg/hr) from Chen et al. (2022), suggesting robust design efficacy. Validation is visually confirmed in the graph, a graph plotting predicted versus actual performance across these machines. The close clustering of our optimal sample's efficiency and throughput with literature values (e.g., within 5-10% of screw press extruder results from Obi et al., 2022) indicates model accuracy. Discrepancies, such as the lower throughput compared to the hydraulic press, are attributable to scale and design constraints, reinforcing the need for context-specific optimization. This validation confirms the model's predictive capability for real-world applications.



	Optimal Sample	Piston-Type Briquetting Machine	Screw Press Extruder	Hydraulic Piston Press	Manual Briquetting Machine	Single-Cylinder Extruder	Vertical Ring Die Briquetting Machine	Screw Press Briquetting Machine	Low-Pressure Manual Press	Multi-Briquetting Machine	Rice Husk Briquetting Machine
Efficiency (%)	79.4607	85.7	75	82	60	70	78	76%	55	65	87%
Throughput (kg/hr)	41.8815	68.56	50	96	25	13	45	35	20	60	45

Figure 8: Graph of Validation of Performance of briquette machines

5. Conclusion

The current study aimed to improve the performance evaluation of charcoal briquette machines using locally made equipment. A detailed review of relevant literature is part of the research to find common problems with the performance and assessment of charcoal briquette. Dimensionless correlations between the variables influencing the machine's energy consumption, throughput, and efficiency were established using the Buckingham Pi theory. Using the Buckingham Pi theorem, the dimensionless analysis revealed three main dimensionless groups that govern the performance evaluation of charcoal briquette machines: the Reynolds number, which denotes fluid flow; the Euler number, which denotes pressure drop; and the Nusselt number, which denotes heat transfer. These dimensionless groups were then used to build empirical models that connected the process parameters to the energy consumption, machine throughput, and oil output.

This study holds significant potential to stimulate regional economies, particularly in rural areas, by fostering job creation through the production and sale of charcoal briquettes and briquetting machines. It also underscores the importance of transforming agricultural residues into valuable energy resources, aiding in sustainable waste management.

5.1 Recommendation

1. Future efforts should focus on refining the briquetting machine design to enhance efficiency and throughput. Addressing identified simulation anomalies, such as unrealistic displacement values, through improved boundary conditions and load specifications will ensure more reliable performance under operational conditions.
2. Further research should explore detailed cost-benefit analyses to assess the economic viability of scaling briquette production. Investigating local market dynamics and subsidies could make the technology more accessible to micro-enterprises, boosting its adoption.
3. A comprehensive evaluation of the machine’s environmental footprint, including emissions during production and use, is advised. This will reinforce its sustainability claims and guide improvements to minimize ecological impact, enhancing its appeal as a green technology.

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