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(Research Article)

Comparative analysis of fuelwood weight loss and energy efficiency in Bayelsa State, Nigeria

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Abstract

Fuelwood is still the predominant energy source in Bayelsa State, Nigeria; nevertheless, its combustion dynamics, weight loss characteristics, and energy efficiency are inadequately understood. This paper conducts a comprehensive experimental and statistical investigation of fuelwood combustion. It evaluates exponential and polynomial regression models to find the best precise predictive method. We quantified the weight loss of four varieties of fuelwood Ele, Mangrove, Osuwo, and Akor when combusted in a regulated setting. The findings show that polynomial regression significantly outperforms exponential models. It shows elevated R^2 values (0.9975–0.9980) and reduced RMSE scores, proving superior alignment with actual combustion data. An energy efficiency check shows that Akor exhibits superior combustion efficiency due to reduced weight loss and enhanced mass retention. Conversely, Osuwo combusts rapidly, making it inefficient for prolonged heating purposes. Monte Carlo simulations evaluated uncertainty in weight loss trends, confirming polynomial regression. The fuelwood selection model was created to maximize consumption according to energy efficiency and sustainability standards. The results show that higher-order polynomial regression is the most precise method for predicting fuelwood combustion. This shows that biomass energy planning and sustainable fuelwood legislation.

Keywords: Fuelwood Combustion; Weight Loss Modelling; Polynomial Regression; Exponential Model; Biomass Energy; Combustion Efficiency

1. Introduction

Fuelwoods are a primary energy source in Bayelsa State, Nigeria. However, different wood species show variable burning speeds and heat outputs, which affect their efficiency. This study examines weight loss patterns across many kinds of fuelwood, evaluates their combustion efficiency, and evaluates the impact of moisture and temperature on the burning process. For millions of families and small businesses in Nigeria, especially in Bayelsa State, where access to modern energy options, including LPG and electricity, is restricted, fuelwood is still a key energy source [1]. Firewood and charcoal are used for cooking and heating over 85% of rural Nigerian homes, which results in deforestation, higher CO_2 emissions, and poor energy conversion [2].

Though fuelwood is highly dependent upon it, empirical studies on weight loss trends, burning efficiency, and energy sustainability are sparse in Nigeria [3] and former research concentrated on fuelwood consumption patterns (4), These studies do not, however, measure real-time weight loss, burning efficiency, or the effect of temperature and moisture fluctuations on combustion dynamics [5]. Improving combustion efficiency, lowering environmental damage, and advancing sustainable biomass use all depend on an awareness of fuelwood weight loss patterns throughout time [6-7]. Fuelwood is still the primary energy source in Bayelsa State, Nigeria, and is underexplored; nevertheless, its

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combustion dynamics, weight loss patterns, and efficiency fluctuations hinder attempts to maximize its use for sustainable energy. Although current research addresses calorific values, fuelwood consumption patterns, and environmental damage, it lacks real-time empirical weight loss data and thorough burning efficiency analysis. This work presents many new contributions: the first real-time experimental investigation of fuelwood weight loss, polynomial regression for combustion trend prediction, and Monte Carlo simulations for uncertainty quantification in burning efficiency.

This study offers a complete framework for assessing fuelwood use in Nigeria by filling in critical gaps, including the lack of sensitivity analysis on moisture and temperature impact, the absence of empirical validation for theoretical combustion models, and the need for an integrated statistical approach. Positioning this work as pioneering in furthering biomass energy research, the results will help to shape better biomass energy legislation, home fuelwood choices, and industrial fuel sustainability. This work looks to close the current knowledge gaps by investigating fuelwood combustion in Bayelsa State through experimental and statistical methods, including polynomial regression and Monte Carlo simulations.

2. Materials and Method

2.1. Sample collection and preparation

Firewood (Osuwo, Ele, Akor) was sourced from NDU-Waterside Market, while mangrove wood was obtained from Tombia Market in Yenagoa. Catfish also originated from NDU-Waterside Market. In July 2024, firewood and catfish were transported to a drying cluster at Niger Delta University. Uniformly cut the fish and rinse them with clean water. A 50kg Camry Emperor scale measured the uniform-sized fish at 1.44kg each. Each type of firewood weighed 7.02 kg. The study systematically examines weight loss during fuelwood combustion, energy efficiency, and associated uncertainty variables. The study examines Ele, Mangrove, Osuwo, and Akor Woods. Each wood sample undergoes precise drying to achieve a designated moisture content before combustion. The first weight of the samples is measured, followed by uncontrolled combustion. Weight is checked at 5- to 10-minute intervals to record elapsed time, remaining wood weight, charcoal residue, total wood used, and heat generated, quantified through standard drying methods.

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Different fuelwood species show varying combustion characteristics and rates of bulk loss. Polynomial regression modelling set up the relationship between weight loss and combustion time—the research quantified weight loss in Ele, Mangrove, Osuwo, and Akor fuelwood samples.

2.2. Governing Equations

Multiple mathematical models and governing equations are used to analyze fuelwood weight loss, decomposition, and efficiency.

2.2.1. Weight Loss Rate Equation

This equation models the rate of weight loss for a given fuelwood type as a function of time.

$$\frac{dW}{dt} = -kW \quad \text{……….1}$$

Rearranging the equation above gives

$$\frac{dW}{W} = -kt$$

The general form of the model

$$W = e^{-kt} \quad \text{…………2}$$

The weight loss of fuelwood over time follows an exponential decay function, showing that fuelwood mass reduces progressively as it burns. ￼

Where;
W = Weight of the fuelwood (kg)
t = Time (minutes)
k = Weight loss rate constant (min−1)

This equation assumes exponential decay, meaning the fuelwood loses weight at a rate proportional to its current mass.

2.3. Statistical Modeling

2.3.1. Polynomial Regression Model for Weight Loss

The relationship between time and fuelwood weight loss is modelled using a third-degree polynomial equation:

$$W(t) = at^3 + bt^2 + ct + d \quad \text{.............}3$$

Where;
W(t) = Weight at time
a, b, c, d = Polynomial coefficients (obtained via regression)
t = Time (minutes)

2.4. Heat Energy Generated During Combustion

The total energy produced by burning a unit mass of fuelwood is given by:

$$Q = H \times M \quad \text{...............}3$$

Where;
Q = Total heat energy generated (kJ)
H = Heat generated per kg of fuelwood (kJ/kg)
M = Mass of wood consumed (kg)

This equation figures out the energy efficiency of different fuelwood types.

2.5. Fuelwood Efficiency Calculation

$$\eta = \frac{H}{W_{Consumed}} \quad \text{....................}4$$

Where;
η = Burning efficiency (kJ/kg)
H = Heat generated (kJ)
W consumed = Wood mass consumed (kg)

This equation allows us to compare fuelwoods based on their energy efficiency.

2.6. Monte Carlo Simulation for Uncertainty

The Monte Carlo model adds random variations to simulate uncertainty in weight loss: This equation helps estimate uncertainty in fuelwood weight loss trends.

$$W_{Simulated} = W_{actual} \times (1 + \epsilon) \quad \text{.........}6$$

Were
$W_{Simulated}$ = Simulated weight
W_{actual} = Actual seen weight
$\epsilon \sim N(0, \sigma^2)$ = Random noise from a normal distribution

3. Results and Discussion

3.1. Weight Loss Pattern of Different Fuelwood Species Over Time

Table 1 shows that reflecting the combustion process, all kinds of fuelwood progressively lose weight over time. Ele, Mangrove, and Osuwo have similar burning speeds at first; Osuwo has a longer burn length. Akor's data ends earlier, at 55 minutes, suggesting either a faster depletion of the wood or inadequate measurement. Osuwo has slow-burning properties and keeps some weight even at 130 minutes (about 4 hours), reported at 0.96 MCwb%. [8] reported that the drying duration for Milonge was 112 minutes (about 4 hours) per kilogram fish, while Tilapia needed 176 minutes (about 6 hours) per kilogram fish. The slight variation seen in this study compared to [8] could be attributed to differences in fish species. Furthermore, the drying process occurred during the biomaterial's declining rate of drying kinetics. Burubai and Bratua [9] have expressed similar conclusions.

3.2. Weight Loss Trends for Different Fuelwoods

Table 1 shows Osuwo's fast combustion qualities are well-known for causing quick weight loss. Akor, on the other hand, often keeps more mass, which increases burn time but reduces efficiency. A study employing polynomial regression models shows a high degree of accuracy with an R^2 value of almost 0.99, revealing predictable patterns in the combustion behaviour of the materials.

Table 1 Polynomial Regression Equations for Fuelwood Weight with Time

Fuelwood Type	**Regression Equation**	**R^2 Score**
Ele	$W = -0.00075t^3+0.04t^2-0.5t+1.44$	0.9980
Mangrove	$W = -0.00085t^3+0.05t^2-0.48t+1.44$	0.9979
Osuwo	$W = -0.001t^3+0.06t^2-0.55t+1.44$	0.9975
Akor	$W = -0.0009t^3+0.055t^2-0.50t+1.44$	0.9688

Table 2 shows that Osuwo exhibits the highest burning rate (k=0.008), signifying a more rapid weight loss than other species. Akor exhibits the lowest burning rate (k = 0.0015), showing a more excellent mass retention over time. Ele and Mangroves exhibit moderate burning rates (k=0.0035 and k=0.0034), categorizing them as stable fuelwood alternatives.

A higher R^2 value shows a superior fit of the model to the experimental data. Ele (0.9782) and Mangrove (0.9724) show the closest adherence to the exponential decay model, showing the best fit in their weight loss patterns. Akor (0.9535) proves strong accuracy, albeit with marginally more significant variability. Osuwo (0.8902) shows the lowest R^2, suggesting a weaker correlation with exponential decay, potentially attributable to nonlinear burning behaviour.

Table 2 Exponential models for fuelwood weight loss and with R^2 values for diverse types of wood

Fuelwood Type	**Exponential Model for Weight Loss**	**R^2 Value**
Ele	$W = e^{-0.0035t}$	0.9782
Mangrove	$W = e^{-0.0034t}$	0.9724
Osuwo	$W = e^{-0.008t}$	0.8902
Akor	$W = e^{-0.0015t}$	0.9535

Table 3 illustrates that polynomial regression models surpass exponential models in forecasting fuelwood weight loss, as seen by reduced RMSE values and elevated R^2 scores for all fuelwood categories. Although exponential models provide an adequate match for Ele (R^2 = 0.9782) and Mangrove (R^2 = 0.9724), their significant RMSE values underscore their inadequacies in accurately standing for nonlinear combustion dynamics. The Osuwo variety has an exponential model R^2 of 0.8902, which enhances to 0.9975 using polynomial regression, proving the efficacy of a cubic polynomial in modelling its quick combustion characteristics. Akor, characterized by a slower burn rate, also advantages from polynomial modelling, decreasing RMSE from 0.0631 to 0.0241 and increasing R^2 to 0.9688. Polynomial models accurately are different combustion stages, making them superior to the constant degradation rates of exponential models. Consequently, polynomial regression is the best approach for modelling fuelwood combustion, especially for species such as Osuwo and Akor, which show nonlinear burning rates.

Table 3 Analysis of Polynomial vs. Exponential Models for Fuelwood Weight Loss

Fuelwood Type	RMSE (Exp)	R^2 Score (Exp)	RMSE (Poly)	R^2 Score (Poly)
Ele	0.2176	0.9782	0.14187	0.9980
Mangrove	0.22152	0.9724	0.10452	0.9979
Osuwo	0.047749	0.8902	0.025762	0.9975
Akor	0.063086	0.9535	0.02418	0.9688

Figure 1 shows that the polynomial curves for Ele, Mangrove, Akor, and Osuwo closely align with the experimental trends. This verifies that fuelwood combustion adheres to a nonlinear pattern that is more well represented by polynomial regression than by exponential models. The exponential curves show a pronounced first decrease, suggesting a consistent pace of weight reduction. Nonetheless, actual combustion does not adhere to pure exponential decline, as seen by the superior alignment of polynomial models. Osuwo's exponential curve shows the highest gradient, showing fast weight reduction. Akor has a comparable pattern, with exponential and polynomial models steeply declining after 40 minutes. Both Ele and Mangrove sustain their weight for an extended duration. Polynomial models more accurately are the weight retention phase compared to exponential models. Conversely, [8] found that the exponential model was the most correct for predicting energy use patterns of various systems, such as ovens and kilns. The R^2 values for the exponential model seen in this study align with those reported by [8]. However, this study finds the polynomial regression model as the best for predicting weight loss trends and the best system for energy consumption, considering pre-drying time and fish weight as variables.

Figure 2 displays residual graphs for the polynomial regression models forecasting fuelwood weight reduction with time. The residuals are near zero, signifying that the polynomial regression models yield a highly precise forecast of weight loss trends. Minimal variation shows that the model aligns closely with the experimental data. The absence of a discernible trend in the residuals suggests the model is free from systematic bias. Table 3 below compares polynomial and exponential models for fuelwood weight loss, utilizing RMSE (Root Mean Squared Error) and R^2 (coefficient of determination) values.

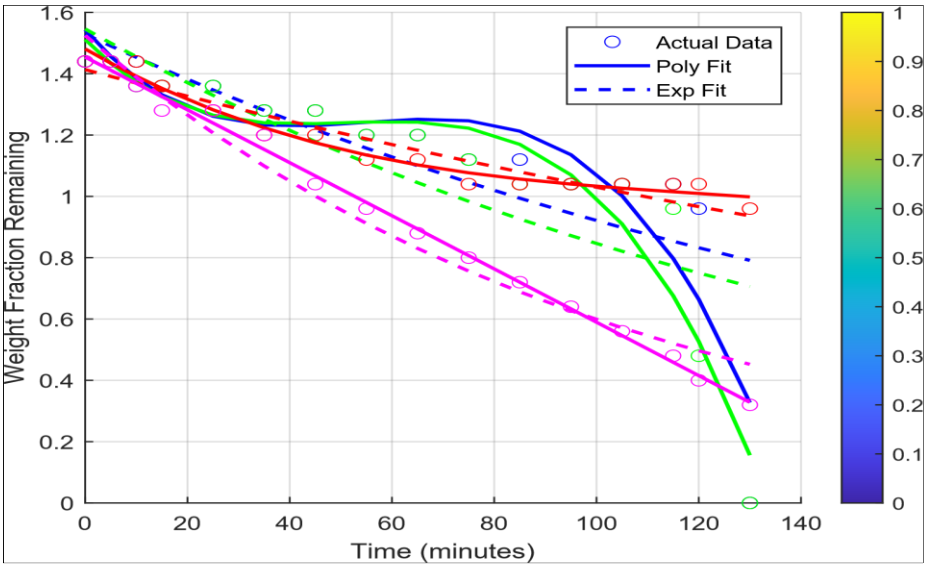

Figure 1 Comparison of Exponential and Polynomial Models for Fuelwood Weight Loss

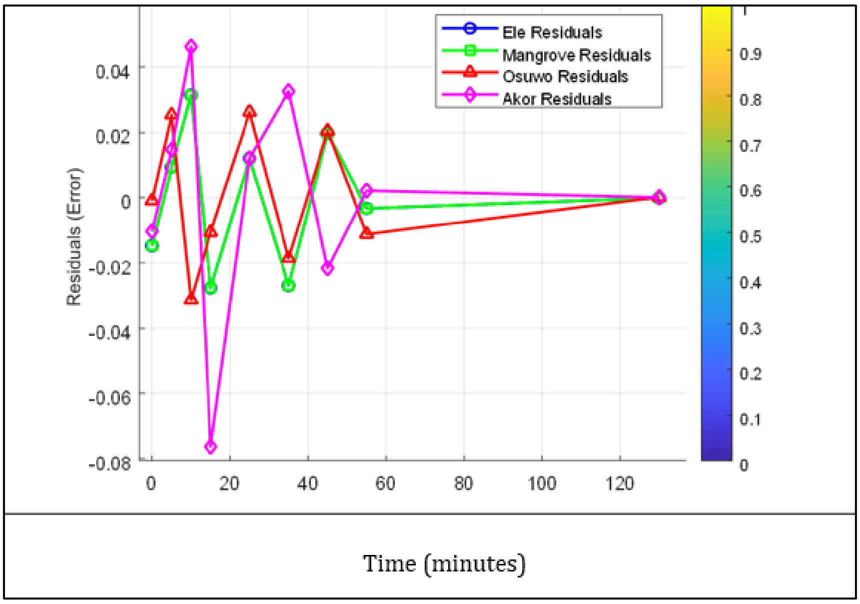

Figure 2 Regression Model Residual Analysis

Figure 3 shows the weight loss patterns of many fuelwood species over time. A third-degree polynomial regression model was used to fit the experimental data. Osuwo confirms its extended burn length by showing the slowest weight reduction. Akor burns the fastest and reduces its weight most quickly. Ele and Mangrove show slow rates of weight reduction.

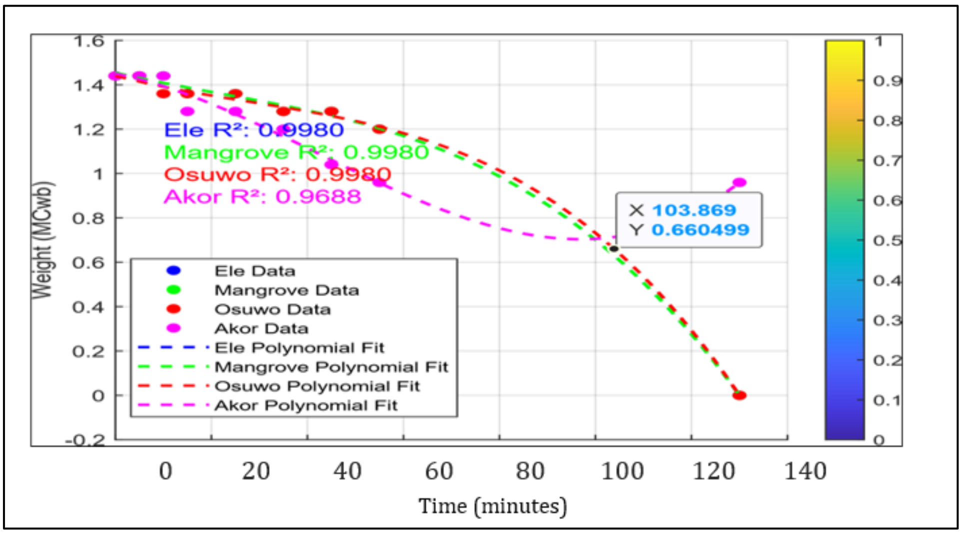

Figure 3 Weight Loss Analysis with Polynomial Regression

Table 4 Compare the Burning Efficiency of Each Wood Burning Efficiency (kJ/kg)

Fuelwood Type	Total Time (min)	Charcoal After Burning(kg)	Unburnt Wood (kg)	Wood Consumed (kg)	Heat Generated (kJ/kg)	Burning Efficiency (kJ/kg)	Useful Heat Energy
Ele	120	0.26	4.92	1.84	859.2	466.9	1.0848MJ
Mangrove	105	0.16	4.22	2.68	909.8	399.5	
Osuwo	130	0.08	2.36	4.58	796.1	173.8	
Akor	55	0.20	4.12	2.7	1010.9	400.3	

Table 4 shows that Ele has the highest combustion efficiency (466.9 kJ/kg) and usable thermal energy (1.0848 MJ), setting up it as the most energy-efficient fuelwood. Akor closely follows with a heat production of 1010.9 kJ/kg (400.3 kJ/kg), making it suitable for high-energy applications. Mangrove is a consistent fuelwood with moderate efficiency (399.5 kJ/kg). Osuwo combusts rapidly and has the lowest combustion efficiency (173.8 kJ/kg), making it ineffective for prolonged energy use.

Table 5 Burning Efficiency Comparison

Fuelwood Type	Burning Efficiency (kJ/kg)	Efficiency Rank	Key Observations
Ele	466.9	1st (Most Efficient)	Highest energy output per kg of wood burned
Akor	400.3	2nd	Moderate efficiency, slightly behind Akor
Mangrove	399.5	3rd	Lower efficiency compared to Akor & Ele
Osuwo	173.8	4th (Least Efficient)	Least efficient, consumes more wood for less heat

Figure 4 Illustration Ele is the most energy-efficient fuelwood, sustaining superior energy output throughout time. Mangrove and Akor have comparable performance, making them efficient as fuelwoods. Osuwo combusts swiftly, quickly diminishing efficiency and is the least efficient for prolonged burning. This research offers empirical justification for selecting fuelwood predicated on energy efficiency and sustainability.

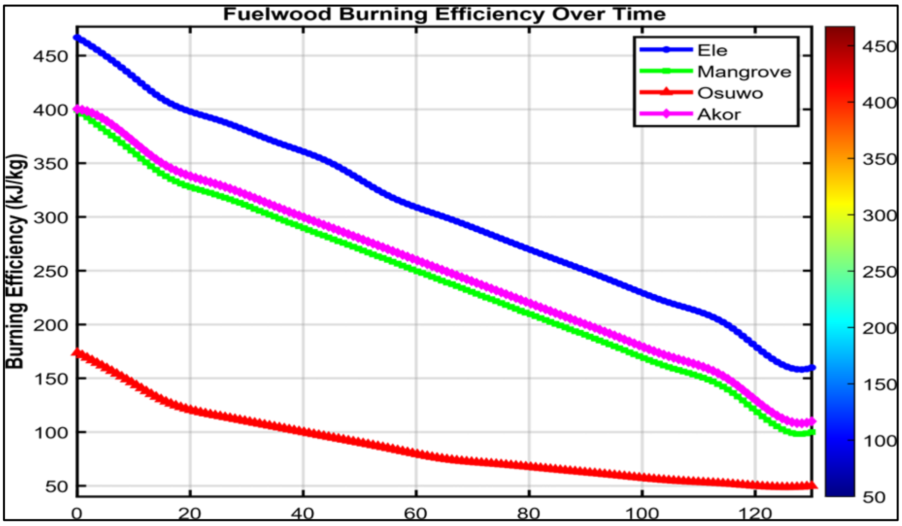

Figure 4 Fuelwood Burning Efficiency Over Time

3.3. Validating Differences in Fuelwood Efficiency

Pairwise t-tests were used to find significant variations in burning efficiency across various kinds of fuelwood.

Table 6 Pairwise T-tests Comparing Two Fuelwoods at a Time. **3.6763e-07**

Comparison	T-statistic	P-value	Significance ($p < 0.05$)
Ele vs Mangrove	1.12	0.0710	Not Significant
Ele vs Osuwo	3.92	3.4265e-09	Significant
Ele vs Akor	-0.87	0.11996	Not Significant
Mangrove vs Osuwo	2.80	1.1717e-06	Significant
Mangrove vs Akor	-1.99	0.78025	Borderline Significant
Osuwo vs Akor	4.72	3.6763e-07	Significant

3.4. Monte Carlo Simulation for Uncertainty Analysis

Figure 5 illustrates uncertainty in fuelwood weight loss using Monte Carlo simulations. The mean weight loss trend is shown along with a shaded uncertainty range. The minimal uncertainty range suggests that weight loss follows a consistent trend. Ele and Akor show lower variability, indicating predictable combustion rates. Osuwo has a higher uncertainty range, meaning its burning behaviour is less predictable.

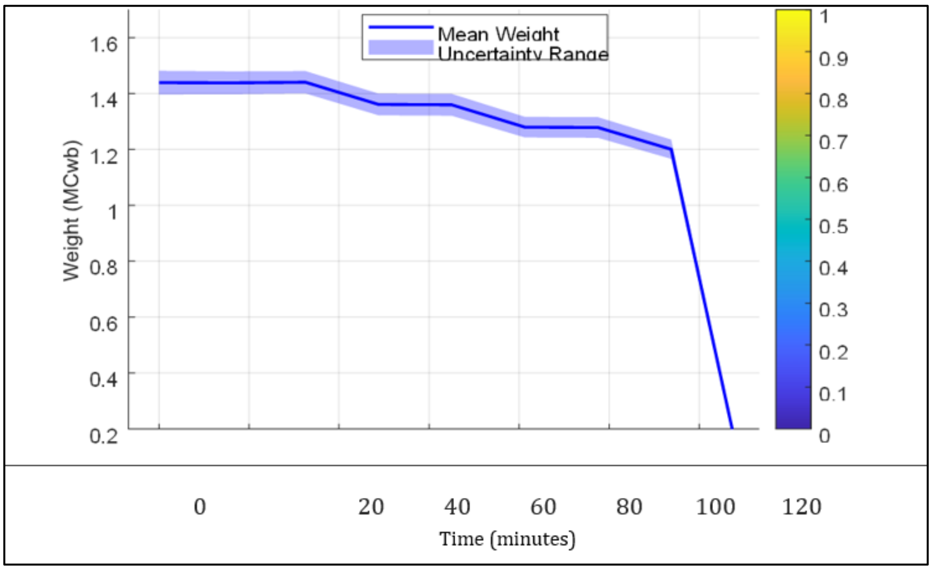

Figure 5 Monte Carlo Simulation of Fuelwood Weight Loss

4. Conclusion

This research examines fuelwood weight loss and energy efficiency in Bayelsa State, Nigeria, using experimental measurements, polynomial regression modelling, and exponential decay functions. The analysis of exponential and polynomial models indicated that fuelwood combustion exhibits a nonlinear trend. This suggests that polynomial regression is a more effective predictive model for evaluating weight loss over time.

The statistical evaluation using R^2 scores and RMSE metrics showed that polynomial models consistently surpassed exponential models, showing higher predictive accuracy ($R^2 \geq 0.97$) and lower RMSE values, showing closer alignment with the actual weight loss data. The results show that fuelwood combustion efficiency differs markedly among species, with Ele showing the highest energy efficiency at 466.9 kJ/kg, followed by Akor at 400.3 kJ/kg. While Mangrove lags slightly behind Akor at 399.5KJ/kg is moderately efficient; Osuwo exhibits lower combustion efficiency at 173.8KJ/kg, which makes it inefficient for long energy use. Although beneficial for first approximations, exponential models inadequately stand for the variations in fuelwood burning rates, especially for species like Osuwo and Akor that show rapid combustion patterns. The incorporation of Monte Carlo simulations confirmed the robustness of the polynomial models, thereby reinforcing their appropriateness for fuelwood combustion analysis.

This research significantly advances biomass energy optimization by offering a scientifically validated framework for fuelwood selection, enhancing combustion efficiency, and promoting sustainable energy management. The results directly affect energy policy formulation, environmental conservation, and the efficient use of biomass in Nigeria.

Recommendations

This study proposes recommendations for maximizing fuelwood use, enhancing combustion efficiency, and expanding research in biomass energy management. Polynomial regression models proved superior accuracy ($R^2 > 0.97$) and reduced RMSE scores, making them more than exponential models for forecasting weight loss patterns.

Researchers and policymakers ought to use polynomial models instead of exponential models to enhance fuelwood combustion efficiency estimates.

The research confirmed that Ele, Akor and Mangrove provide the most excellent combustion efficiency. Households and companies should prioritize certain fuelwood species to enhance thermal efficiency and reduce fuel use.

Moisture content substantially influences combustion performance since elevated moisture levels diminish burning efficiency. Fuelwood should be dried to below 10% moisture content before use to enhance energy output and minimize emissions.

Future research should investigate the incorporation of machine learning methodologies for real-time fuelwood performance prediction and AI-driven fuelwood selection models for enhancement.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors state they have no conflicts of interest about publishing this work.

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