Heliyon 10 (2024) e40875

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Optimization of economics of biomass fuel mix for boilers in tea processing through response surface methodology

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ARTICLE INFO

Keywords:
Biomass
Fuel cost
Moisture
Energy optimization
Tea processing

ABSTRACT

Fuelwood is the primary source of heat energy for tea processing, but its availability is declining due to population growth and logging restrictions. This study aimed to optimize the economics of biomass fuel mixtures for tea processing boilers by integrating macadamia nutshells as a supplementary fuelwood. The objective was to develop a cost-effective fuel mix strategy using Response Surface Methodology (RSM) and MATLAB simulations. The methodology involved proximate and ultimate analyses to assess the energy potential of fuelwood and macadamia nutshells. Various scenarios of moisture content and wood availability were simulated to determine the necessary quantities of macadamia nutshells to address fuelwood shortages. RSM was then applied to optimize the fuel mix by minimizing costs while maximizing energy efficiency. Key findings revealed that macadamia nutshells have a higher bulk density (680–745 kg/m^3) and lower moisture content (7.86–10 %) than eucalyptus wood (322–358 kg/m^3, 15–50 % moisture content). Additionally, macadamia nutshells have a superior calorific value (21,296.56 kJ/kg) compared to eucalyptus (18,765.24 kJ/kg), though they are more expensive (USD 0.10/m^3 vs. USD 0.04/m^3). The regression analysis showed that moisture content significantly increased fuel costs (18 % per unit increase), while wood availability reduced costs by 17 % per unit increase. The quadratic model ($R^2 = 0.9995$) confirmed these interactions. The study supports the use of macadamia nutshells as a viable alternative or supplementary fuel source, enhancing the sustainability of tea processing operations.

1. Introduction

Tea *(Camellia sinensis),* which is globally cherished beverage, has been a significant part of Kenya's socioeconomic growth since its introduction in 1903 [1]. Despite the success of the tea industry, there are multiple challenges it faces including escalating fuel costs [2]. Tea processing, which includes withering, rolling, fermentation, and drying, is primarily focused on moisture removal during withering, rolling, and drying stages, reducing the moisture content from 80 to 3 % on a wet basis [3,4]. Over 90 % of the thermal energy needed for this process is provided by fuelwood, which serves as the primary energy source [5]. It is regarded as a renewable, carbon-neutral energy source widely used in both domestic and industrial settings in Kenya. Moreover, it has a significant impact on reducing greenhouse gas emissions [6,7] associated with the production of the beverage.

The quality of fuelwood is crucial for energy efficiency, particularly during combustion, and is determined by factors such as

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https://doi.org/10.1016/j.heliyon.2024.e40875
Received 9 August 2024; Received in revised form 18 November 2024; Accepted 2 December 2024
Available online 4 December 2024

moisture content (MC), volatile matter (VM), fixed carbon (FC), ash content (A), calorific value (CV) and bulk density [8,9]. High moisture content can significantly reduce the gross calorific value (GCV) of fuelwood, increase transportation costs, and raise drying expenses [10]. High ash content decrease combustion efficiency, leading to increased disposal costs due to accelerated equipment wear, frequent maintenance, a larger volume of ash management, strict environmental compliance, decreased boiler efficiency, and operational challenges [11]. On the other hand, a higher FC improves the GCV, making ignition easier, while a higher VM to FC ratio enhances the ignitability of biomass [12].

Building on the pursuit of sustainability in the biomass sector, green energy solutions can also be beneficial for steam systems which are crucial part of nearly all major industrial processes today [13]. Industry sectors that depend on steam systems include manufacturing, district heating systems, power plants, food and beverage, and refineries. In the past, fossil fuels have been a major component of steam generation, but resulted in significant carbon emissions and environmental concerns. By incorporating sustainable practices, such as utilizing biomass as a clean energy resource, steam generation can be transformed into a more environmentally friendly process [13,14].

Further, recent studies have explored the potential of renewable energy, particularly solar power, in sustainable steam generation [15]. There is also a growing interest in utilizing agricultural biomass as a renewable energy resource through various technologies [16]. While biomass is regarded as a carbon-neutral energy source, policymakers are tasked with developing strategies to effectively incorporate it into the energy mix to ensure environmental sustainability [17]. Research has extensively covered various facets of biomass combustion, including its processes, heating value, ash properties, and comparisons with other fuels, as well as co-firing with coal and biomass transportation logistics [10,17–19]. Despite these advancements, the co-combustion of biomass with diverse characteristics remains underexploited.

Challenges in sourcing affordable, high-quality and dry fuelwood due to limited land availability have necessitated the optimization of the supply chain to mitigate transport uncertainties [20,21]. Transport and logistic optimization models entail critical components such as managing fuelwood demand and supply, storage at intermediate facilities, considerations of fuelwood quality deterioration, inter-modal distribution for long-distance transport, operational transportation planning, and fuelwood pre-processing [22]. The uncertainty in fuelwood supply chains is compounded by factors like varying MC, ash content, volatile matter, and lower heating value [22,23]. Seasonal fluctuations of fuelwood availability also affect the quality, quantity, and cost of fuelwood, particularly concerning moisture content and the need for drying and storage [24–26].

As sustainable alternatives many sectors including the tea sector are actively exploring green energy sources and alternative biomass fuels. This shift has raised interests among researchers and investors [27,28], and there has been an increase in biomass supply chain modelling studies within the research sphere. Such studies provide in-depth analysis of logistics pricing [29] and are focussed in designing an efficient supply chain networks for the smooth transportation of materials from the source to the end user. Although biomass itself is not very expensive, logistics represent a significant portion of the overall costs [30]. Various modeling approaches have been used to enhance the efficiency and sustainability of biomass supply and logistics. These methods range from the general field of mathematical optimization to more specialized techniques, such as uncertainty analysis through stochastic optimization [31], sensitivity analysis [32], and quality analysis with some studies employing a combined approach [33]. Among these, a novel multi-objective mixed integer linear programming model has been implemented, highlighting the substantial impact of biomass procurement costs and maximum transportation distance on the supply chain's expenses and structural configuration [34]. In a similar vein, another advanced mathematical model was developed to assist decision-makers in navigating uncertainties surrounding biomass feedstock availability, aiming to reduce the overall costs of the biomass supply chain [35]. These models demonstrate the diverse strategies employed to address different challenges within the sector.

The Kenya Tea Development Agency (KTDA) faces significant challenges in securing a sustainable fuel supply due to the national ban on fuelwood procurement from forests, implemented in 2018. This has exacerbated issues related to the quality, availability, sustainability, and cost of fuelwood, leading to increased competition, higher prices, and reduced profit [12–14]. Despite exploring alternative energy sources like solar, wind, and biomass briquettes, economic hurdles remain due to high initial setup costs, fuel price fluctuations, and inconsistent biomass supply chains. Suryani et al. [36] notes that the high cost of biomass briquettes limits their use in Kenya's tea industry, while Thirunavukkarasu & Sawle, 2022) [37] highlights that the economic feasibility of hybrid energy systems depends on operational scale and local energy market conditions. These factors continue to pose financial challenges in the tea processing sector. Significant research has been conducted on biomass combustion processes, heating value, and supply chain optimization. However, the co-combustion of biomass with varying characteristics, such as macadamia nutshells and eucalyptus fuelwood, remains largely unexplored. The Kenyan tea processing industry is currently grappling with rising fuel costs and restrictions on fuelwood procurement, lacking an optimized biomass fuel mix strategy to address economic and sustainable energy challenges. This study aims to develop a cost-effective fuel mix strategy by utilizing stochastic assessment and optimization techniques to assess the calorific value and availability of fuelwood and macadamia nutshells. By doing so, this research offers a sustainable solution to the economic hurdles faced by the tea industry.

2. Materials and methods

2.1. Experimental procedures

The study used eucalyptus fuelwood and macadamia nutshells sourced from Makomboki Tea Factory in Murang'a County, Kenya (located at 0°48′14″N 36°50′39″E and an altitude of 2160 m). The experimental analysis was conducted at the Kenya Industrial Research and Development Institute (KIRDI) in Nairobi and Lab Works East Africa in Nairobi. The mix biomass fuel was characterized by species, density, moisture content, and cost. Data on seasonal biomass availability were obtained from the factory's historical records. MATLAB (Version 2020b) was employed for simulation and stochastic data generation, while Design Expert software (Version 13) was utilized for optimization.

2.1.1. Biomass characterization

In order to optimize the fuel mix for tea processing boilers, it was crucial to thoroughly characterize the biomass materials being used. The primary objective of this assessment was to analyze the key physical properties of the two main biomass options: eucalyptus wood and macadamia nutshells. The characterization process involved a thorough analysis of the moisture content, proximate analysis, ultimate analysis, and calorific value of the biomass. These parameters are crucial in determining the heating value and, subsequently, the efficiency of the combustion process. The annual production of macadamia nutshells in the study area was approximately 84,380 kg, with peak production between February and July. The biomass characterization in this study was specifically tailored to reflect the actual characteristics of the biomass used in the boilers at the factory under investigation. The analyses ensured that the results accurately represent the conditions and performance of the biomass in real-world operations.

2.1.2. Proximate analysis

The proximate analysis was carried out following the ASTM D 3172-73(84) method [38] Moisture content was determined as per ASTM E871-82 [39], volatile matter and ash content were assessed based on ASTM E872-82 and ASTM D1102-84 [40,41], respectively. The measurements were conducted on a mass basis, with the biomass weight recorded before and after each test to calculate the mass difference. The biomass was weighed after drying at 105 °C for 24 h to determine the weight loss from moisture evaporation. The remaining sample was then heated to 950 °C for 7 min and weighed to determine the mass loss from volatile matter. Ash content was determined by combusting the remaining material at approximately 700 °C in oxygen for approximately 2 h. Fixed carbon was calculated using equation (1). A muffle furnace (Thermo Scientific Lindberg/Blue M Moldatherm Box Furnace) was used for the tests

$$FC(\%) = 100 - MC(\%) - Ash(\%) - VM(\%) \tag{1}$$

2.1.3. Ultimate analysis

In the ultimate analysis, samples of fuelwood and macadamia nutshells were burned in an Element Analyzer (Leco CHNS-932, USA) to measure the weight percentages of carbon, hydrogen, nitrogen, and sulfur. This procedure determined the total carbon, hydrogen, and nitrogen simultaneously from the same sample in the analyzer. The ASTM standards were applied to ensure precision in measurement: ASTM E 777 [42] for Carbon and Hydrogen, ASTM E 775 [43] for Sulfur, and ASTM E 778 [44] for Nitrogen. The percentage of oxygen was calculated by subtracting the combined percentages of carbon, hydrogen, sulfur, nitrogen, and ash from 100. This analysis provides a convenient method to report the primary organic elemental composition of the analyzed biomass fuels.

2.1.4. Calorific value analysis

The gross calorific value of biomass fuels was determined using an oxygen bomb calorimeter (model XRY-1A, China), following ASTM standard procedure D5865 [45]. The biomass samples were shredded, weighed (ranging from 0.999 to 1.0 g) using an analytical balance, and placed into the stainless steel bomb cup using a spatula. To ensure calibration accuracy, 1 g of benzoic acid was added to the calorimeter. A combustible wire, 10 cm in length, was measured and connected to the bomb's positive and negative terminals, traversing the sample. The bomb was then sealed within the oxygen bomb chamber, and oxygen was introduced at pressures between 2.8 and 3.0 MPa via a pipe; 3000 g of distilled water was also added to the calorimeter. The ignition wires were connected, and both the power and stir switches were activated. The ignition button was pressed to start the experiment. The calorimeter automatically documented the temperature rise and was switched off upon reaching the peak temperature. The calorific value was calculated using equation (2), where E represents the standard energy value of the bomb, ΔT denotes the temperature change, Φ is the constant heat of

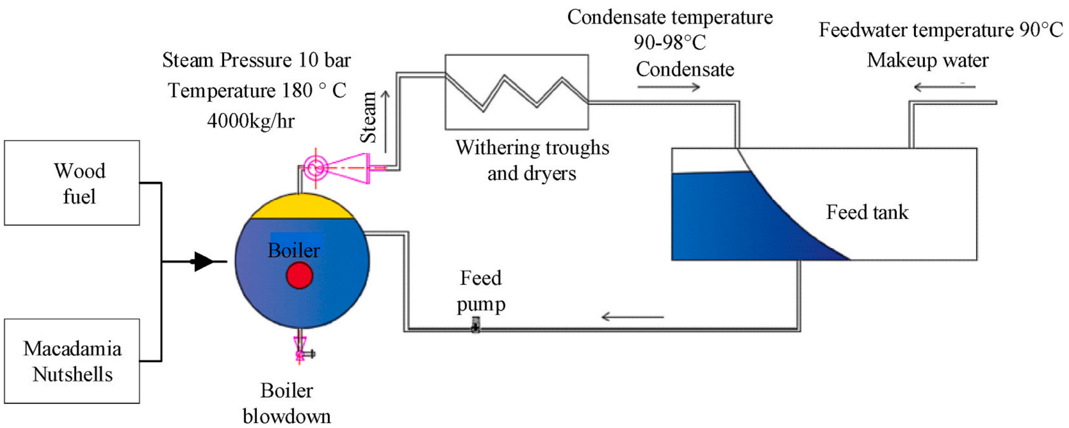

Fig. 1. Steam system generation and utilization.

combustion of the wire, V indicates the correction term for heat exchange with the surrounding environment, and M is the mass of the sample.

$$QCV = \frac{E\Delta T - \Phi - V}{M} \tag{2}$$

2.2. Simulation procedures

2.2.1. Mathematical modelling

The simulation procedures were based on a mathematical model that replicated the operational dynamics of biomass-fueled boilers in tea processing factories. The factory uses a Thermax woodpac (model wp-3p-40, India) horizontal three pass biomass boiler, known for its high efficiency due to the three-pass heat exchange design. The model considered key parameters like steam pressure, temperature, and energy requirements per operational cycle to provide an accurate framework for assessing fuel performance The specific boiler under examination had been designed to produce 4000 kg of saturated steam per hour at a pressure of 10 bar and a temperature of 180 °C, which are crucial for the withering and drying stages in tea production. This operational configuration necessitates a significant energy input, estimated at 18.7 GJ per hour [46]. The steam system setup is illustrated in Fig. 1.

For analysis, the moisture content of macadamia nutshells was assumed to be constant, resulting in a stable calorific value as determined by proximate analysis. In contrast, fuelwood was sourced from various suppliers, leading to variability in wood quality and moisture content. Fig. 2 illustrates the biomass feedstock (fuel wood and macadamia) and the biomass boiler used in the study. The calorific value of fuelwood, however, fluctuated with its moisture content, as demonstrated in equation (3), which is derived from established empirical relationships in the field of biomass energy. This relationship is commonly used to estimate the calorific value of wood fuels based on their moisture content and aligns with data from standard fuel analysis sources. Specifically, the net calorific value (NCV) is a function of the moisture content (MC), as supported by Dyjakon [47].

Fig. 2. Biomass feedstock (fuel wood and macadamia) and biomass boiler.

$$NCV_{MC} = \frac{19 \times (1 - MC) - 2.44 \times MC}{1} \tag{3}$$

2.2.2. Simulation model in MATLAB environment

The simulation relied on the Monte Carlo approach to generate stochastic variables that represented moisture content and wood availability. This approach allowed accounting for the natural variability and uncertainty in these parameters. Forty (40) sets of moisture content and wood availability values were generated, covering a range from 12 to 50 % and 50 and 100 %, respectively. Each set underwent 20 iterations, resulting in a comprehensive dataset for optimization analysis. The MATLAB environment was employed to manage various tasks: inputting key variables such as biomass type, availability, and moisture content; running the Monte Carlo simulations to generate stochastic variables and model the variability in biomass properties; and calculating outputs including fuel mix ratios, total energy input, and fuel costs.

2.2.3. Cost and energy output calculations

The simulation served two key purposes: evaluating the energy output of the biomass mix and assessing the economic feasibility by analyzing the associated costs. The cost per unit of biomass, denoted as c, and the quantity available, denoted as i, were critical variables in the economic assessment of the fuel mix. To factor in the uncertainties associated with biomass sourcing, a stochastic variable ξ was introduced, representing the probability of variations in both biomass quality defined by its net calorific value and its availability. The cost of biomass is determined by its availability and quality. Low-quality biomass, with a lower NCV, requires a larger quantity to meet energy output targets, resulting in higher consumption and overall costs. On the other hand, high-quality biomass, with a higher NCV, is more efficient, reducing the required quantity and lowering costs. The model's objective function was twofold: to maximize the energy output of the fuel mix and to minimize the associated purchasing costs subject to constraints of availability and moisture content. This was modelled using a probabilistic approach, where different scenarios were generated to account for variability. In the model, N is the total number of scenarios generated, ξ is the scenario representation for the stochastic variable, p_ξ is probability of the scenario of each stochastic variable, $P_{i,\xi}$ is the stochastic biomass quantity from source i based on scenario ξ, and $P_{NCV,\xi}$ is the stochastic low heat value of the biomass source in relation to moisture content based on scenario ξ. The model aimed to maximize energy output through equation (4), which considered the stochastic variables for biomass quantity and NCV, while minimizing cost through equation (5), which focused on the stochastic variables for biomass cost. The available biomass was constrained by equation (6), while moisture content was addressed by equation (3).

$$Max \sum_{i=1}^{2} i \sum_{NCV=1}^{2} NCV \sum_{\xi}^{N} p_\xi P_{i,\xi} P_{NCV,\xi} \tag{4}$$

$$Min \sum_{ci=1}^{2} ci \sum_{\xi}^{N} p_\xi P_{ci,}\xi \tag{5}$$

Subject to.

Quantity of biomass available

$$available\ biomass = \sum_{1}^{2} i \tag{6}$$

In addition, Table 1 outlines the criteria for optimizing the fuel mix, which involved minimizing moisture content (targeted between 0.1217 and 0.4997), ensuring wood availability (set at 0.75), and minimizing the cost of the energy mix (falling between 5755.11 and 11385). Each of these variables was given equal importance (rating of 5), as they were all critical to the optimization process. The reliability of wood availability, consistently above 75 % throughout the seasons based on historical data, further supported the optimization's effectiveness in ensuring a steady supply for the energy mix and improving overall cost-efficiency.

The optimization involved an iterative algorithm that evaluated a cost fuel mix, adjusting the contributing variables within their defined ranges to achieve the best possible combination of moisture content and wood availability for the optimum cost of the energy mix.

Table 1
Optimization criteria.

Name of Variable	Goal	Lower Limit	Upper Limit	Importance
Moisture content (θ)	Minimize	0.1217	0.4997	5
Wood availability(α)	is target = 0.75	0.5	1	5
Cost of energy mix (C)	Minimize	39.13	77.42	5

2.3. Analytical procedures

2.3.1. Regression analysis

Regression analysis played a key role in the study by providing a quantitative framework to evaluate the impact of moisture content and wood availability on biomass fuel mix costs. Using data from simulations, a regression model was developed to establish the relationships between these variables and overall fuel mix costs. The analysis aimed to quantify the effects of moisture content and wood availability on costs. By employing multiple regression techniques, the model identified significant predictors of cost, assessed the strength of these relationships, and estimated their impacts. The coefficients obtained from the regression offered insights into how changes in moisture content or wood availability could influence the cost of the fuel mix. This analytical approach was essential for guiding optimization strategies and ensuring decisions were supported by robust statistical evidence.

2.3.2. Response surface methodology

This study also utilized response surface methodology (RSM) for experimental design, employing statistical and mathematical techniques to optimize processes influenced by multiple variables [48]. RSM was specifically applied to optimize moisture content and biomass availability, which are crucial factors in managing fuelwood and macadamia nutshells to minimize the total cost of the fuel mix. The experimental setup used a 2k full factorial design with Design Expert (Version 13), performing 800 randomized runs to explore how the independent variables affect the response. The analysis employed a second-order model, often referred to as the "Imperial equation" (Equation (8)) [49], to capture both linear and non-linear interactions between the variables.

In this model, Y represents the response variable (cost of the fuel mix), β_0 the Intercept of the model, indicating the expected mean value of Y when all x_i (predictors) are zero. The model includes linear terms ($\sum_{i=1}^{k} \beta_i x_i$) where the coefficients β_i quantify the individual effects of each variable (moisture content and availability). It also includes interactive terms, ($\sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j$), with coefficients β_{ij} representing the effects of interactions between moisture content and wood availability variables. Additionally, the quadratic terms ($\sum_{i=1}^{k} \beta_{ii} x_{ii}^2$) model non-linear relationships, indicating curvature in the response surface. and Lastly, the error term (ε) accounts for any variation in Y not explained by the predictors. The optimization goal was to reduce the wood's moisture content while maintaining wood availability at 75 %, in order to reduce the overall cost of the fuel mix. The second-order model provided a detailed analysis of the response surface, capturing the complex interactions between moisture content and availability that affect the fuel mix's economic performance.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \varepsilon \quad (8)$$

2.4. Model validation

Model validation was conducted to ensure the robustness and accuracy of the predictive models used in this study. The experimental design for optimizing biomass combustion integrates methodologies from RSM and stochastic programming, drawing from established models in the fields of bioenergy supply chains, biomass combustion characteristics, and optimization under uncertainty. The validation of the results involves comparative analysis with existing literature on bioenergy optimization, focusing on economic feasibility, supply chain dynamics, and biomass combustion characteristics. Previous research by Ref. [50] on economic and operational feasibility [51], on supply chain dynamics, and [52] on biomass combustion characteristics are referenced for further insights.

3. Results and discussion

3.1. Biomass characterization

Table 2 presents results summarizing key operational variables used in optimization of the biomass fuel mix in the boilers. The results show that mean moisture content, wood availability and cost of energy mix were 0.3085 ± 0.1108, 0.7478 ± 0.1375 and USD 59.58 ± 8.60, respectively. The results in Table 2 form the foundation for the subsequent analysis, linking theoretical models to practical financial implications for sustainable biomass fuel use.

Table 3 compares the characteristics of eucalyptus wood and macadamia nut shells used in tea processing. Eucalyptus wood had a moisture content range of 15–50 %, indicating variability that can impact energy yield, as noted in literature [53], In contrast, macadamia nut shells have a narrower moisture range of 9.8–10 %, suggesting more consistent levels and potentially more predictable energy output, as supported by Ref. [54]. In terms of average density in a dry state, eucalyptus wood has a lower density of 358 ± 30 kg/m^3 compared to macadamia nut shells with a higher density of 745 ± 25 kg/m^3. This aligns with findings from Ref. [55] for eucalyptus and [56] for macadamia nut shells, indicating that the higher density of macadamia nut shells results in greater energy per

Table 2
Descriptive statistics of optimization variables for biomass fuel mix.

Variable	Moisture content (%)	Wood availability (%)	Energy mix cost (USD)
Mean	30.85 ± 11.08	74.78 ± 13.75	59.58 ± 8.60.

Table 3
Characteristics of eucalyptus wood and macadamia nut shells.

Species of biomass	Moisture content range (%)	Average density dry basis (kg/m^3)	Cost (USD/m^3)
Eucalyptus Wood	15–50	358 ± 30	0.04
Macadamia nutshells	9.8–10	745 ± 25	0.10

unit volume, making them more efficient for storage and transportation. Regarding cost, eucalyptus wood is priced at 0.04 USD/m^3, making it a more economical choice than macadamia nut shells at 0.10 USD/m^3. The higher cost of macadamia nut shells may be justified by their higher density and lower moisture content, offering higher energy efficiency.

3.2. Proximate ultimate and calorific value analyses

The proximate, ultimate, and calorific value analyses of eucalyptus wood and macadamia nutshells as biomass fuels are presented in Fig. 3(a), (b), and (c), highlighting the impact of the biomass source on the fuel properties. The proximate analysis indicates that eucalyptus wood had a moisture content of 12.46 %, while macadamia nut shells have a lower moisture content of 7.86 %. This is consistent with previous studies by Ref. [57]), which reported a moisture content range of 10.5–14.4 % for eucalyptus wood and [58], which found a lower moisture level of 8 ± 0.1 % in macadamia nut shells. Both eucalyptus wood and macadamia nut shells exhibit high volatile matter content, with values of 85.25 % and 84.94 %, respectively, which is advantageous for efficient combustion and energy production. These values align with [59] stating that the volatile matter content of biomass materials typically falls between 70 and 85 %. The ash content is lower in macadamia nut shells (0.25 %) compared to eucalyptus wood (0.66 %), consistent with findings by Ref. [60], documenting ash content of 0.76 ± 0.24 for eucalyptus wood and [61]), noting low ash content in macadamia nut shells (0.2 %). The fixed carbon content is 6.95 % for macadamia nut shells and 1.63 % for eucalyptus wood, indicating the amount of combustible carbon remaining after volatile matter removal.

The ultimate analysis reveals that eucalyptus wood contains 51.06 % carbon, 4.82 % hydrogen, 40.49 % oxygen, and 0.00 % sulfur, while macadamia nut shells contain 49.65 % carbon, 5.43 % hydrogen, 41.73 % oxygen, and 0.64 % sulfur. These values are in line with [60] for eucalyptus wood and [62] for macadamia nut shells, reporting similar ranges for carbon content. The higher carbon content in eucalyptus wood (51.06 %) compared to macadamia nut shells (49.65 %) suggests a potential for higher energy content in eucalyptus wood. However, the negligible sulfur content in eucalyptus wood (0.00 %) compared to macadamia nut shells (0.64 %) is beneficial for reducing SO2 emissions, contributing to cleaner combustion.

The calorific value analysis indicates that macadamia nut shells have a higher heating value (HHV) of 21.30 MJ/kg, compared to 18.77 MJ/kg for eucalyptus wood, supporting findings by Refs. [63,64] reporting calorific values of 18.5–19.23 MJ/kg for eucalyptus

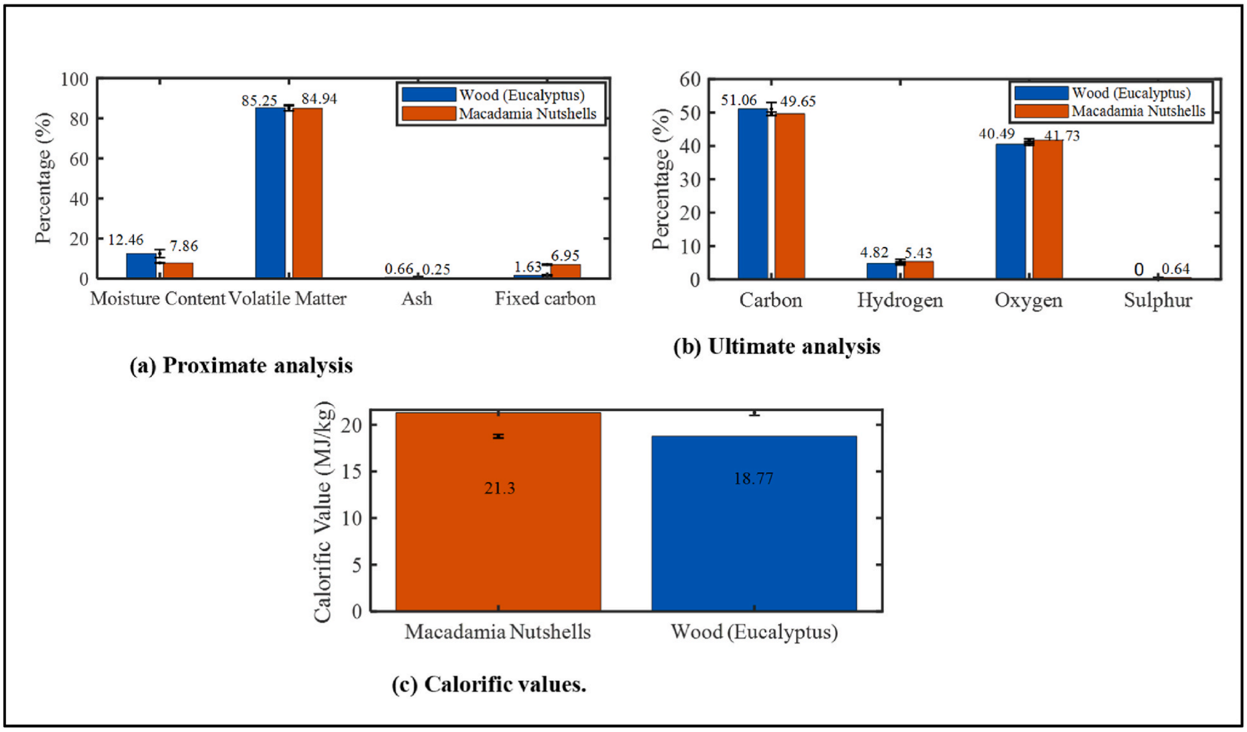

Fig. 3. Biomass fuel analysis; (a) Proximate analysis, (b) Ultimate analysis, (c) Calorific values.

wood and 18.78–26.02 MJ/kg for macadamia nut shells. The analysis reveals that macadamia nut shells possess a higher calorific value due to their lower moisture content, higher fixed carbon, and low ash content. Furthermore, the ultimate analysis shows that eucalyptus wood contains a slightly higher carbon content at 51.06 % compared to 49.65 % in macadamia nut shells. However, macadamia nut shells have higher hydrogen and oxygen content than eucalyptus wood, indicating greater energy potential. These elements, in conjunction with carbon, act as active reactants in the combustion process, enhancing energy production.

3.3. Simulation

3.3.1. Mathematical modeling and stochastic simulation

The simulation analysis used mathematical models and stochastic simulations to assess the performance dynamics of various biomass fuel mixes under different operational conditions. The study examined how fluctuations in moisture content and wood availability could affect energy output and economic viability, generating a comprehensive dataset for optimization. For eucalyptus wood, the study found that moisture content ranges from 0.132 to 0.408, with a negative correlation between moisture content and calorific value, decreasing from 16.49 MJ/kg to 11.25 MJ/kg. This aligns with previous research, such as [65] which showed that higher moisture content reduces the calorific value of biomass fuels, impacting energy conversion efficiency during combustion.

The availability of eucalyptus wood fluctuates between 0.56 and 0.98 %, resulting in energy outputs ranging from 10,449 to 17,657 MJ and associated costs varying from USD 23.34 to 53.37. In comparison, macadamia nut shells have energy outputs ranging from 1912.3 to 7592.7 MJ, with required masses between 89.8 and 356.52 kg and costs from USD 9.16 to 36.37. The total cost for the energy mix of eucalyptus wood and macadamia nut shells ranges USD 44.14 to 59.89, showcasing the economic advantages of using a combination of these biomass types. This is consistent with [66]who highlighted the economic viability of macadamia nut shells as a biomass fuel due to their high heating value (21.12 MJ/kg) and low ash content (1.6 %), making them a cost-effective option for industrial fuel use (see Table 4). The data indicates that macadamia nut shells, with their stable moisture content and high calorific value, offer a more consistent energy output and cost efficiency compared to eucalyptus wood. Leveraging the lower costs of eucalyptus wood and the high energy content of macadamia nut shells, this combination optimizes energy production while managing costs effectively, making it a financially viable choice for biomass fuel for boilers.

Such data is essential for stakeholders considering biomass-based energy production, offering a clear comparison of energy potential and costs for wood and macadamia, both individually and in combination. It encapsulates economic considerations alongside energy yields for these biomass energy resources.

3.4. Analytical results

3.4.1. Regression analysis

Table 5 shows the results of the regression analysis for the model. The analysis reveals a highly significant overall model p-value of 0.0001, indicating a rejection of the null hypothesis that there is no relationship between the dependent variable (total cost of the fuel mix) and the independent variables (moisture content of wood and wood availability). This confirms that the full quadratic model, incorporating both moisture content of wood and wood availability, significantly impacts the total cost of the fuel mix. The p-values for the linear terms associated with the moisture content of wood and wood availability are both less than 0.01, signifying their significant influence on the cost of the fuel mix. Additionally, the p-value for the quadratic term related to the moisture content of wood is also less than 0.01, further supporting its substantial effect on the total cost. However, the quadratic term for wood availability has a p-value of 0.756, indicating that it does not significantly affect the cost of the fuel mix.

The standard error (SE) measured the accuracy of the coefficient estimates, with smaller standard errors indicating more precise estimates. The 95 % confidence interval (CI) provided a range within which we can be 95 % confident that the true value of the coefficient lied. The variance inflation factors (VIFs) are also included in the table, with VIFs below 10 considered acceptable [67] to

Table 4
Simulation results for eucalyptus wood and macadamia nut shells.

Eucalyptus wood						**Macadamia nut shells**						**Total cost of energy mix (USD)**
MC	CV (MJ/kg)	Availability (%)	Energy (MJ)	Mass (kg)	Cost (USD)	MC	CV (MJ/kg)	Availability (%)	Energy (MJ)	Mass of (kg)	Cost (USD)	
0.13	16.49	0.72	13434	814.7	27.7	0.08	21.3	0.28	5240.8	246.09	25.11	52.82
0.13	16.47	0.69	12900	783.2	26.63	0.08	21.3	0.31	5774.8	271.16	27.67	54.31
0.13	16.46	0.88	16486	1001.5	34.05	0.08	21.3	0.12	2189.5	102.81	10.49	44.55
0.14	16.39	0.90	16763	1023	34.78	0.08	21.3	0.10	1912.3	89.8	9.16	43.96
0.16	16.02	0.59	11083	691.9	23.52	0.08	21.3	0.41	7592.7	356.52	36.38	59.91
0.23	14.71	0.84	15684	1066.3	36.26	0.08	21.3	0.16	2990.8	140.44	14.33	50.60
0.28	13.67	0.56	10449	764.1	25.98	0.08	21.3	0.44	8226.5	386.28	39.42	65.41
0.30	13.22	0.75	13991	1058.7	36	0.08	21.3	0.25	4684.1	219.95	22.44	58.46
0.31	12.77	0.98	18299	1432.9	48.72	0.08	21.3	0.02	375.9	17.65	1.80	50.54
0.36	12.15	0.67	12516	1029.8	35.01	0.08	21.3	0.32	6159.2	289.21	29.51	64.54
0.41	11.25	0.95	17657	1569.7	53.37	0.08	21.3	0.59	1018.7	47.83	4.88	58.27

Table 5
Regression analysis for the quadratic model predicting total cost of the fuel mix.

Source	B	SE B	95 % CI (LL-UL)	SS	df	MS	F-value	p-value	VIF	Significance
Intercept	66.43	0.0166	66.40–66.46	75622.98	5	15124.60	231900	<0.0001	–	Significant
Wood moisture Content (θ)	11.80	0.0155	11.76–11.83	37837.97	1	37837.97	580200	<0.0001	1.01	Significant
Wood availability (α)	−11.20	0.0165	−11.23–−11.17	30099.62	1	30099.62	461500	<0.0001	1.01	Significant
($\theta\alpha$)	3.93	0.0280	3.87–3.98	1279.53	1	1279.53	19620.17	<0.0001	1.02	Significant
(θ^2)	3.30	0.0302	3.24–3.36	779.35	1	779.35	11950.52	<0.0001	1.01	Significant
(α^2)	−0.01	0.0320	−0.0728 – 0.0529	0.0063	1	0.0063	0.0967	0.756	1.01	Not Significant
Residual				51.78	794	0.0652				
Total				75674.76	799					

indicate no significant multicollinearity in the model. Furthermore, Table 5 presents the unstandardized coefficients of the coded factors B, showing the expected change in the response for a unit change in a factor value while keeping other factors constant. The coded variables are shown in equation (9), utilizing Response Surface Methodology (RSM), where θ is the moisture content of wood, α is wood availability, and C is the cost of the fuel mix.

$$C = 66.43 + 11.80\,\theta - 11.20\,\alpha + 3.93\theta\alpha + 3.30\,\theta^2 - 0.01\alpha^2 \tag{9}$$

This equation illustrates the relationship between the predictors and the response, emphasizing the significant contributions of the linear and interaction terms, with the quadratic term for wood availability deemed not significant.

Table 6 shows the predicted R^2 of 0.9993 which closely aligns with the Adjusted R^2 of 0.9993. This strong alignment indicates that the model parameters effectively explain the variation in the dependent variable, which is the total cost of the fuel mix. Therefore, the model holds significant practical value. Additionally, the low coefficient of variation of 0.3790 % suggests high precision and reliability of the experiment [54,55].

3.4.2. *Response surface methodology*

Response Surface Methodology (RSM) was utilized to optimize the biomass fuel mix by investigating the relationship between input variables moisture content and wood availability and output response fuel mix cost. This approach involved a methodical examination of the response surface with the objective of reducing costs. From the data that was stochastically generated in MATLAB, RSM enabled the determination of the ideal levels of moisture content and wood availability to achieve the most economical and effective biomass fuel mix. The analysis encompassed the creation of contour plots and response surfaces, which visually depicted the correlation between the variables and the response, providing a clear understanding of how variations in the variables impact the results. Fig. 4 shows the contour of how wood availability and moisture content affect the total cost of the fuel mix. When wood availability is low, the usage of macadamia nutshells increases to compensate for the shortage, thereby raising the cost due to their higher price. Similarly, using wood with high moisture content also leads to a cost increase. This happens because more energy is consumed as latent heat of vaporization to reduce the moisture, necessitating the use of additional fuelwood to meet the minimum energy requirements for operating the boiler.

The resultant 3D response surface evaluating how various combinations of independent variables influence the desirability of the model are presented in Fig. 5. It was noted that the model's desirability increased with a decrease in the moisture content of the fuelwood and an increase in its availability.

The study also included 3D response surface and contour plots to analyze how different combinations of independent variables affect the cost of the fuel mix as depicted in Fig. 6. It was observed that the cost increases with higher moisture content in the fuelwood and decreases with less availability of the fuelwood. This increase in cost is attributed to the higher consumption of fuelwood, needed to account for the latent water of vaporization of water and the greater use of macadamia nutshells to compensate for the energy deficit, which are costlier options.

3.5. *Discussion*

The economic assessment of biofuel supply chains conducted by Ref. [50] supports the economic validation of this study. Their analysis of the profitability of biofuel networks under varying biomass pricing conditions provides a context for comparing the current

Table 6
Model properties.

Model properties	Value
Mean	67.40
Std. deviation	0.2554
Coefficient of variation (%)	0.379
R-squared	0.9993
Adjusted R-squared	0.9993
Predicted R-squared	0.9993

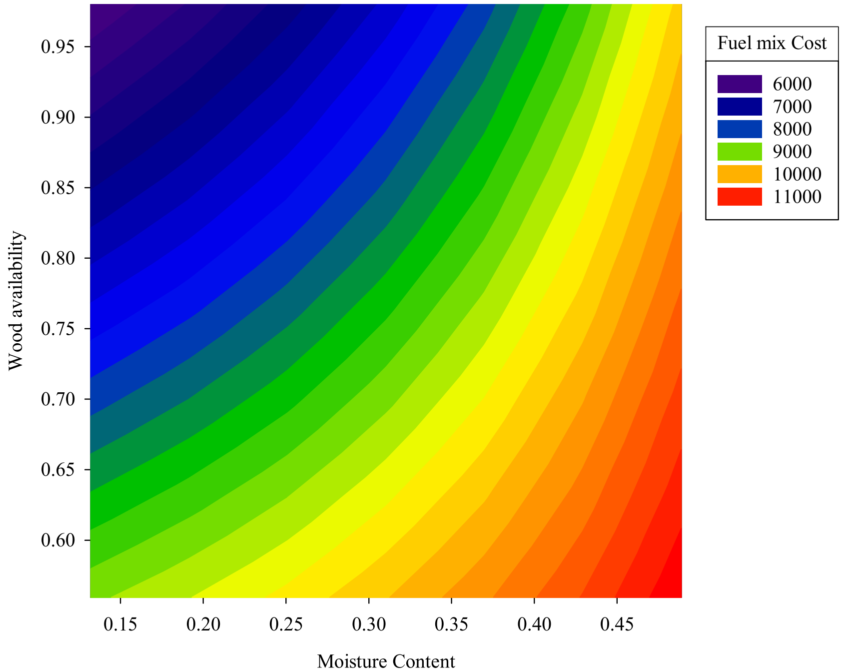

Fig. 4. Effect of moisture content and wood availability on the fuel mix cost.

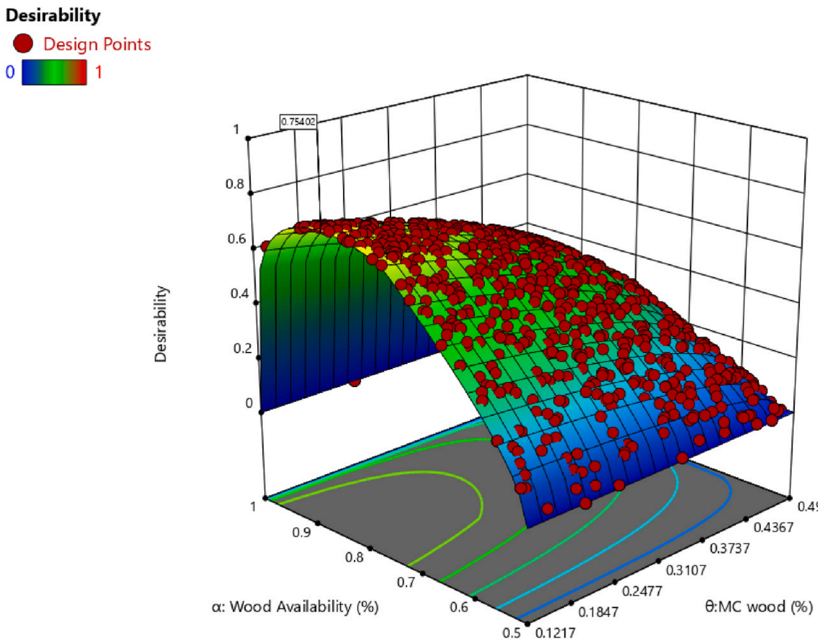

Fig. 5. The 3D surface for desirability, wood availability and moisture content of wood.

study's findings on the cost-efficiency of using macadamia nut shells for biomass combustion. The results in this study align with their findings on supply chain cost dynamics, confirming the economic feasibility of optimized biomass utilization. Additionally [51], present a framework for managing changes in fuel mix within district heating systems, which is similar to the current study's focus on optimizing biomass mix. The model prediction results from this study compares well with their findings on fuel mix efficiencies, demonstrating its effectiveness in real-world energy system applications. Regarding biomass combustion characteristics [52], provide insights into energy content variations and optimization strategies for biomass fuel mixtures. The calorific value and reactivity profiles of eucalyptus reported by Ref. [52] serve as benchmarks for analysis. By understanding how proximate and ultimate compositions

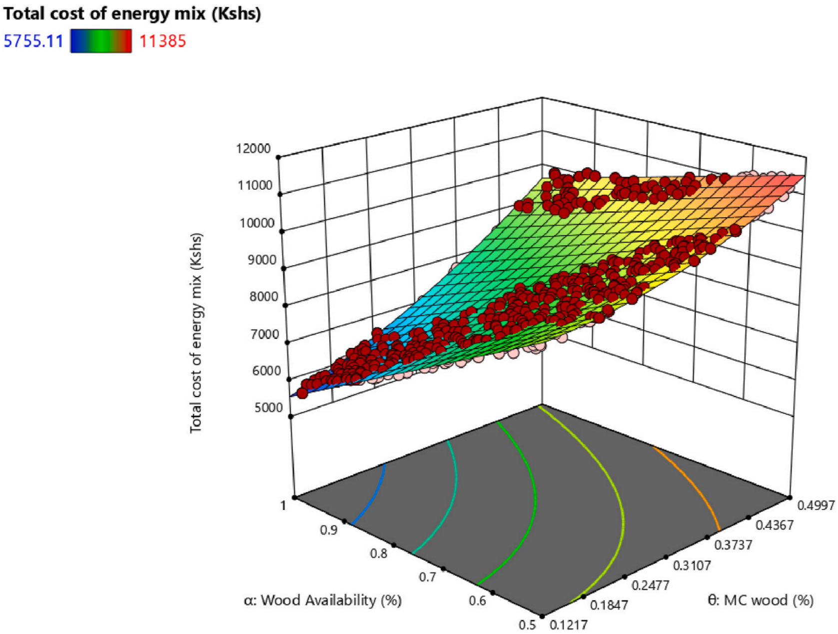

Fig. 6. The 3-D Surface and Contour Plot for cost of energy mix, wood availability and moisture content of wood.

influence these parameters, this study optimizes the proportions of macadamia nut shells to achieve desired energy outputs efficiently.

4. Conclusions

This study has successfully outlined an optimized biomass fuel mix strategy to tackle the issue of fuelwood scarcity in tea processing. The experimental findings demonstrate that macadamia nutshells exhibit a superior calorific value of 21,296.56 kJ/kg and an ideal moisture content range of 7.86–10 %, leading to enhanced energy efficiency compared to eucalyptus wood. The simulations have revealed crucial interdependencies; for example, a one-unit increase in moisture content correlates with an 18 % rise in fuel mix cost, while higher wood availability reduces costs by 17 %, emphasizing the need for a delicate cost management balance. The analytical outcomes, supported by robust regression analysis and RSM, have resulted in an optimized fuel mix that ensures economic and environmental sustainability. The highly predictive model, with an R^2 value of 0.9995, confirms the significant impact of the studied variables on the energy mix cost. The inclusion of macadamia nutshells in the fuel mix has been quantitatively validated as a viable alternative, meeting the calorific requirements of tea processing while offering a cost-effective solution to the fuelwood challenge in the tea industry.

CRediT authorship contribution statement

Veronica K. Ngunzi: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Christopher L. Kanali:** Writing – review & editing, Supervision, Conceptualization. **Gareth M. Kituu:** Writing – review & editing, Supervision, Investigation. **Erick K. Ronoh:** Writing – review & editing, Visualization, Supervision, Methodology, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readability. After using this tool/ service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors affirm that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the work reported in this work.

Acknowledgements

The authors are grateful to the African Development Bank for the financial support to carry out this work. The authors also wish to express their gratitude to Makomboki Tea Factory in Kenya for providing the necessary data.

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