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MULTI-RESPONSE OPTIMIZATION OF THE CHARACTERISTICS OF WOODEN FUEL SOURCES FOR BOILER APPLICATIONS

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ABSTRACT. Various kinds of biomass fuels are used for boiler and other kinds of thermal applications. The presence of moisture, ash and calorific value are known to be the most significant quality factors which influence the effective performance of a biomass fuel for a plant. The reasons for measuring the above mentioned quality factors are to perform the economic analysis and to control the combustion. The relevant industries are interested to obtain a method for predicting these quality factors quickly and consistently; and also to identify biomass fuels containing optimal level of these factors. In the present work, five different biomass fuels have been considered such as rubber wood, eucalyptus wood, mixed wood (tamarind tree and neem tree woods), palm shell with fiber and juliflora woodchips. The moisture content in the considered woods have been found to be 27.74 wt.%, 37.78%, 30.19 wt.%, 23.26 wt.% and 37.01 wt.% respectively. The main objective of this work is to maximize the efficiency of production. Grey relational analysis has been carried out to optimize the moisture content, ash content and calorific value in order to achieve cost savings and fuel efficiency. Also, the economic analysis has been done with the operational costs.

KEY WORDS: Biomass, Fuels, Energy, Boiler, Optimization

INTRODUCTION

Biomass fuels are sustainable and renewable. The reason for selecting the biomass fuels is that they release carbon dioxide at the same level that they absorbed during the photosynthesis process. Coal and gas are also renewable energy sources. They need many years to form, whereas biomass fuels can be produced within very few years. There are many kinds of biomass fuels such as wood, agricultural residues, and industrial residues. Mostly wood is preferred and used in industrial applications as they are considered to be sustainable, renewable and economical. There are many types of woods such as rubber wood, julio-flora wood, mango nuts, palm shell with fiber, silk cotton wood, paddy husk, and eucalyptus wood.

Salognia *et al.* had conducted a maintenance study on a biomass - fired - organic rankine cycle-co-generative heat power plant. The authors mainly focused on the operation cum maintenance of the waste wood conversion plant. The gross electric power generation capability of the plant was 1.0 MW [1]. Yao *et al.* had investigated the heat transfer on stationary bed materials in a circulating fluidized bed boiler. The mean bed temperature was measured to be 729.2 °C at the end of the simulation. The results revealed that the stationary bed materials flawlessly dissipated heat [2]. Oswald *et al.* had studied about the controlled optimal combustion in biomass-fired boilers. The objective of the investigation was based on the efficient combustion process as well as reduced harmful emission. [3]. Oliveiraa *et al.* had quantified the performance of a cyclonic boiler using biomass sawdust. That study was performed by using *Cedrela fissilis* biomass as sawdust. The cyclonic combustor has a rotational flow inside the chamber and reactants are injected tangentially at the external diameter [4]. Vrána *et al.* had evaluated the combustion process for small scale biomass fired boilers. The control algorithm applied for these boilers provided optimal efficiency with minimum impact on the environment [5]. Garcíaa *et al.* had studied the size-up, monitor, and performance optimization of a 120 kW capacity boiler. The

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authors had considered different factors relevant to the biomass combustion in a commercial pellet boiler [6]. Dzurenda *et al.* had analyzed the effect of moisture content present in the wood on the thermal load with the aid of flue gases released by a boiler. In the proposed work, the heating of flue gases was clearly analyzed in the temperature range of 120 to 200 °C, released by the boiler when the wood with 10 to 60 wt.% moisture content was combusted [7]. Zhang *et al.* had performed an optimization study on the performance measures of an open absorption heat pump. In the proposed work, two-stage regeneration and part regeneration open absorption heat pump systems were projected [8]. Bahadori *et al.* had analyzed the impact of moisture content in the biomass on the combustion of sugarcane bagasse in boilers. This work considered a biomass combustion system (large scale) for producing heat and hot water and steam. This system had the capability of working with the biomass fuels containing comparatively large amount of moisture [9]. Zhang *et al.* had analyzed the performance of biomass gasification connected with a coal-fired boiler system for different loading conditions. The model was developed, verified, and used to test the significance of co-firing straw gas on the performance of the coupled boiler system [10].

Tarelho *et al.* had carried out emissions mitigation using control of biomass feeding for a biomass boiler used in industrial application. The researchers had gathered data related to the biomass feeding control with the operating conditions. Two distinct methods were considered to control the biomass feeding. The first method consisted of a manually controlled biomass feeding; and the second one contained an automatic control with a screw-feeder [11]. Yang *et al.* had designed an optimal waste heat recovery system for a supercritical CO_2 coal-fired power plant in order to improve the dust collection efficiency [12]. Orang *et al.* had analyzed the impact of feedstock moisture content on biomass boiler operation. The carried out research work focused on the performance of the stoker-grate type biomass boilers used in pulp and paper mills. The mean level of moisture content present in the feedstock burned in biomass boilers in pulp mills was typically about 40% to 50%. When the amount of moisture in the feedstock suddenly gets increased due to rain, the furnace temperature will get decreased. This would have suppressed the combustion, in turn lower the steam production capacity of the boiler [13]. Oischinger *et al.* had carried out an optimization study for the fractional collection efficiency of electrostatic precipitators used in biomass-fired boiler. In the carried out investigation, the three commercially available electrostatic precipitators used for the purpose of dust removal in flue gases getting released from biomass-fired boilers were analyzed and reported in detail [14]. Wang *et al.* had employed fuzzy logic approach to test the efficiency of a boiler used in power plants. The authors had clearly expressed the data-driven soft computing method for measuring boiler efficiency. It was confirmed that the developed fuzzy model achieved a balance between the boiler efficiency and NOx emission under different loading conditions [15]. Yin *et al.* had stated that effective biomass fuels are being prepared in three methods viz., first-generation preparation method, second-generation preparation method and third-generation preparation method. The third-generation preparation method of biomass fuels includes extra thermal pre-treatment for increasing the energy density and grindability of the feedstock [18].

From the literature survey, it was understood that several research works have been carried out by the researchers on different kinds of biomass fuels for boiler applications. Optimization studies have been done on the performance characteristics of various kinds of biomass fuels. With this motivation, the present research work has been planned to optimize the calorific value, cost savings and fuel efficiency of five different biomass fuel materials for boiler application.

EXPERIMENTAL

Selection of materials

Based on the literature survey and the research reports, the majorly used five biomass fuels have been considered in the present work such as rubber wood, eucalyptus wood, mixed wood, palm shell with fiber and woodchips. The green density value, compression strength (parallel to grain), Modulus of elasticity and Modulus of rupture values of the rubber wood are known to be 800 kg/m^3, 32 N/mm^2, 9240 N/mm^2 and 66 N/mm^2, respectively. Eucalyptus wood has 732 kg/m^3 mass density, 13909 N/mm^2 modulus of elasticity and 111 N/mm^2 modulus of rupture. Tamarind wood and neem wood have been combinedly considered as mixed wood in the present study. Wood chips are normally small pieces of woods. In the present study, wood chips obtained from the *Prosopis julilora* wood have been considered. The considered types of wood are shown in Figures 1(a), 1(b), 1(c), 1(d) and 1(e).

Figure 1. (a) Rubber wood, (b) Eucalyptus wood, (c) Mixed wood, (d) Palm shell with fiber, and (e) Prosopis juliflora wood chips.

Determination of the moisture content

All the experimentations (measurement of moisture content, ash content and GCV) have been carried out at Madura Coats Pvt. Ltd., Ambasamudram, Tamil Nadu, India, at normal atmospheric conditions.

The moisture present in the chosen biomass fuels measured with the aid of infrared radiation (IR) moisture balance when that IR moisture balance is connected to the power supply. It carries two knobs, the first one is in the right position, and the second one is in the left position. Both the knobs are completely closed during the testing time. After that, both of them are kept at open position at the top and the fuel for the process is fed. After that the IR lamp is switched on and then it is processed to set the temperature until 110 °C. Finally, the final reading of the moisture content level of the fuel is noted.

Determination of ash content using muffle furnace

The ash content of biomass fuel was measured using a muffle furnace. Muffle furnace is a kiln for high-temperature applications, often for the manufacture of pre-loaded box-type oven or furnace connecting glass, enamel coatings, pottery and soldering and brazing articles. They are also used in many research facilities.

The muffle furnace has ceramic fiber blanket and panel insulation on the inside of the furnace. The ceramic part absorbs the high temperature. A crucible is kept inside the muffle furnace and then heated up to the initial temperature of 550 °C for 30 min. Then the crucible is weighed. After that the biomass fuel to be tested of two gram mass is taken in the crucible and it is kept inside the furnace. The temperature of the furnace is increased gradually up to 815 °C for 1 hour. The weight difference is noted, from which the amount of ash content is found out.

Determination of gross calorific value (GCV) using bomb calorimeter

The bomb calorimeter includes a bomb pot, calorimeter, stirrer, thermometer, air jackets, oxygen cylinder, battery and a crucible. Biomass fuels of known weight are burned in a closed pot in the presence of excess oxygen and the combustion products are cooled to assess the GCV of the fuel. The bomb calorimeter used in the present study is shown in Figure 2.

Figure 2. Bomb calorimeter used for the present work.

Working principle of bomb calorimeter

Weigh the biomass fuel and keep it in the crucible. Keep the crucible in the ring of the electrode. Tie the resistance wire between electrodes such that it touches the fuel. Add about 10 mL of distilled water at the bottom of the bomb pot and fix the lid tightly to the bomb by screwing. Fill the bomb with oxygen at a pressure of 25 kg/cm^2. Place the Bomb in a calorimeter. Add a known volume of water in the calorimeter so that the Bomb gets immersed in the water. Place the calorimeter in the water jacket over the plastic studs. Keep the thermometer and stirrer in the water of the calorimeter. Put the plastic cover on the top and make electrical connections from the battery to electrodes. Operate the stirrer for 5 min and note the initial temperature of the water. Pass the current for about 5-10 s to heat the wire so that the fuel catches fire. Note the maximum temperature reached. After that, note the average rate of fall of temperature per minute and the time is taken for reaching the initial temperature. The heat liberated by burning fuel is equal to the heat absorbed by water and calorimeter.

RESULTS AND DISCUSSION

Determination of moisture content

The moisture content present in the biomass fuels has been determined by calculating the mass difference between the burnt and un-burnt fuel. The results are tabulated in Table 1. The moisture content present in the individual biomass fuels are represented as a bar chart and presented in Figure 3. From the bar chart, it was observed that the palm shell with fiber biomass fuel contained minimal amount of moisture content.

Table 1. Moisture content presented in the considered biomass fuels.

S. No.	Biomass fuel	Initial mass of the fuel (g)	Final mass of the fuel (g)	Wt.% of moisture content
1	Rubber wood	4.780	3.454	27.74
2	Eucalyptus wood	4.855	3.021	37.78
3	Mixed wood	4.601	3.212	30.19
4	Palm shell with fiber	4.824	3.702	23.26
5	Wood chips	4.766	3.002	37.01

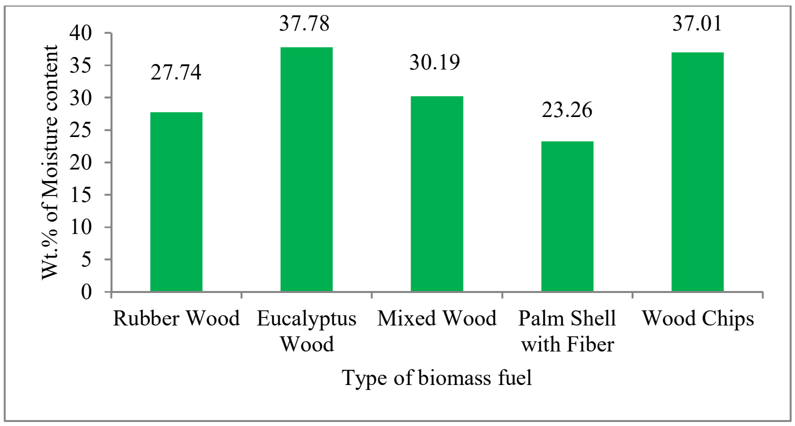

Figure 3. Moisture content present in the considered biomass fuels.

Determination of ash content

Ash content presented in the biomass fuels was predicted using the formula as given in Equation (1). The results are tabulated in Table 2. The moisture content present in the individual biomass fuels are represented as a bar chart and presented in Figure 4. From the bar chart, it was observed that the palm shell with fiber biomass fuel contained maximum amount of ash content.

$$\text{Wt.\% of ash content} = \frac{(M_3 - M_4)}{(M_2 - M_1)} \times 100 \quad (1)$$

where, M_1 – Mass of the empty crucible, M_2 – Mass of the crucible with fuel, M_3 – Mass of the crucible with ash, M_4 – Mass of the cleaned empty crucible. M_3–M_4 : mass of the ash, M_2–M_1 : mass of the fuel.

Table 2. Ash content presented in the considered biomass fuels.

S. No.	Biomass fuel	M_1 (kg)	M_2 (kg)	M_3 (kg)	M_4 (kg)	Wt.% of ash content
1	Rubber wood	35.29	37.29	35.3824	35.29	4.62
2	Eucalyptus wood	35.29	37.29	35.3818	35.29	4.59
3	Mixed wood	35.29	37.29	35.3813	35.29	4.57
4	Palm shell with fiber	35.29	37.29	35.3846	35.29	4.73
5	Wood chips	35.29	37.29	35.3818	35.29	4.59

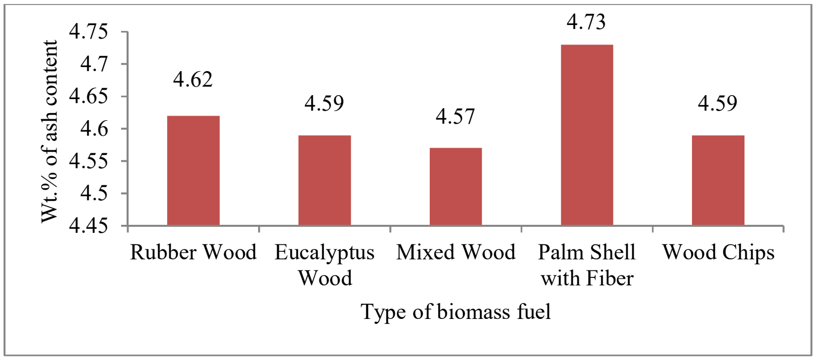

Figure 4. Ash content present in the considered biomass fuels.

Determination of GCV

The gross calorific values of the considered biomass fuels were calculated using the formula as shown in equation (2). The results are tabulated in Table 3. The calculated values of the gross calorific values of the considered biomass fuels are represented as a bar chart and presented in Figure 5. From the bar chart, it was observed that the palm shell with fiber biomass fuel had maximum GCV.

$$GCV = \frac{(W+w)(T_2-T_1)-(T_f+a)}{X} \quad (2)$$

where, W – Mass of water in the calorimeter, w – Mass of water equivalent of the calorimeter set, $(T_2–T_1)$ – Rise in the temperature of water, T_f – Fuse wire correction, a – Acid correction, X – Mass of the fuel in grams.

The following data are the common data for all the five biomass fuels: mass of water in calorimeter (W) = 300 g, water equivalent of calorimeter set (w) = 2100 g, total corrections (fuse wire, cotton thread, acid) = 30.32 cal., and mass of the fuel (X) = 1.050 g.

Table 3. GCV values of the considered biomass fuels.

S. No.	Biomass fuel	Initial temperature, T_1 (°C)	Final temperature, T_2 (°C)	Rise in temperature (°C)	GCV (kcal/kg)
1	Rubber wood	27.3	28.46	1.16	2622.55
2	Eucalyptus wood	26.81	27.99	1.18	2668.27
3	Mixed wood	26.23	27.38	1.15	2599.70
4	Palm shell with fiber	26.8	28.48	1.68	3811.13
5	Wood chips	27.1	28.27	1.17	2645.41

Economical analysis

Economic analysis is used to provide a financial estimate for the intended project. In order to carry out the economical analysis, two different categories of operational costs, variable cost and fixed cost are normally considered. For a better financial estimation of the feasible projects, the operational costs are generally considered to be fixed cost, so that commodity and energy prices do not fluctuate; and all parameters that can be considered mutable over the time periods considered.

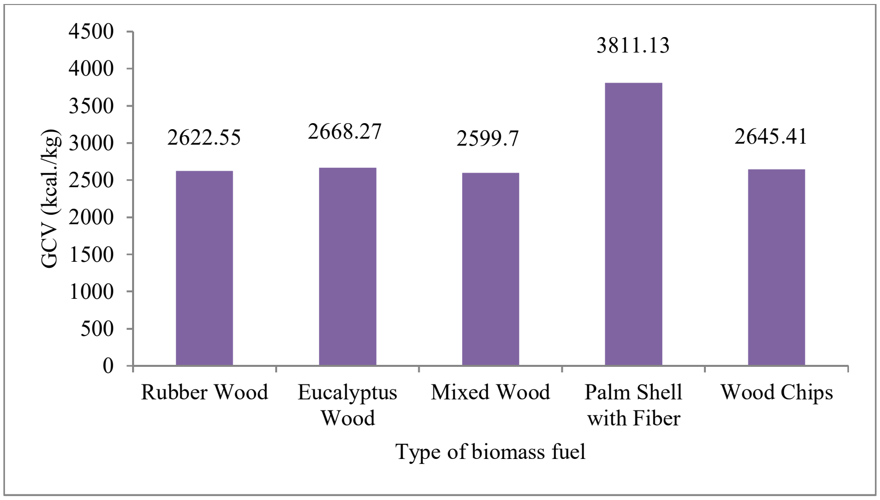

Figure 5. GCV values of the considered biomass fuels.

Feedstock cost

A specific amount of raw material (feedstock) is required to produce the required heat. The formula being used for the calculation of feedstock cost is in equation (3). The annual expenses for the biomass fuels can be easily calculated using this formula. It is critical to be mentioned that each country has exclusive feedstock costs which in particular relies upon at the availability of the fuel and the forest regions that every country is covered. The rate of feedstock is one of the predominant factors which can impact the feasibility of a biomass project. For estimating the feedstock demand, the boiler efficiency and energy content need to be estimated.

$$\text{Feedstock cost} \;=\; \text{Demand (tons/year) x Feedstock price} \tag{3}$$

Demand

Demand of a biomass fuel is that how much amount of fuel has been taken to the boiler process. The demand is quantified using the formula as given in equation 4.

$$\text{Demand} \;=\; [\text{Boiler capacity} \;\times\; \text{Energy content x Running hours}]/\text{Boiler's efficiency} \tag{4}$$

Energy content (%) = [GCV x Organic dry matter content (%)] – [Energy required to dry 1 kg of water x Moisture content (%)] (5)

Organic dry matter content (%) = [100%–Wt.% of moisture content] x [100%–Wt.% of ash content] (6)

The following data were noted for the calculation of demand and feedstock cost. Boiler capacity: 15 TPH. Boiler's efficiency: 78.9%. Energy required to dry 1 kg of water: 589 kcal/kg.

The calculated values of feedstock cost for each individual biomass fuel considered for the present study are presented in Table 4.

Table 4. Feedstock cost for the biomass fuels.

S. No.	Biomass fuel	1 Ton for feedstock price (Rs)	1 year feedstock cost = (demand× feedstock price) (Rs)
1.	Rubber wood	3300	99,000,000
2.	Eucalyptus wood	4000	120,000,000
3.	Mixed wood	3100	93,000,000
4.	Palm shell with fiber	4500	135,000,000
5.	Wood chips	3600	108,000,000

Grey relational analysis (GRA)

One of the main objectives of the proposed study is to identify the wood which contains optimal level of moisture content, ash content and GCV (gross calorific value). For that, various multi-objective optimization techniques are available. From the literature survey, it was found that grey relational analysis (GRA) technique is one among them and this technique is very easy to follow [19]. So, GRA technique has been utilized in the present study. In GRA, the initial step is normalizing the responses of each output factor. Under two criteria, the normalized values have been calculated: 'smaller-the better' and 'larger-the better'. In the current work, the formula used for calculating the normalized values for GRA under 'smaller the-better' criterion is as follows [20]:

$$x_i(k) = [\text{Max } y_i(k) — y_i(k)] \div [\text{Max } y_i(k) — \text{Min } y_i(k)] \quad (7)$$

The formula used for calculating the normalized values for GRA under 'smaller the-better' criterion is as follows:

$$x_i(k) = [y_i(k) — \text{Min } y_i(k)] \div [\text{Max } y_i(k) — \text{Min } y_i(k)] \quad (8)$$

In equation 8, i = 1, 2, 3...n. where 'n' is the number of experiments conducted, k = 1, 2...m. where 'm' is the number of output factors chosen for the study.

Grey relational coefficient (GRG) values were calculated using equation 9. Grey relational grade values are the mean values of GRC values computed for each experimental run. Then, the experiments were ranked in such a way that the experiment holding the maximum value of GRG was ranked as '1' [16].

$$\text{GRC}, (k) = [\Delta_{min} + \varsigma\Delta_{max}]/[\Delta_0(k) + \varsigma\Delta_{max}] \quad (9)$$

where, $\Delta_0(k)$ – deviation sequence value ζ is known as the distinguishing coefficient. In the Normalized values calculation, smaller-the better criterion has been considered for the moisture content and ash content values; and larger-the better criterion has been considered for the GCV values.

The deviation sequence values have been calculated by finding the difference between the each individual normalized value and their maximum value [17].

The normalized values (NV) of the moisture content, ash content and GCV values, the deviation sequence (DS) values, the grey relational coefficient (GCV) values, the grey relational grade (GRG) values of the considered biomass fuels and their ranking order are presented in Table 5, where, 'M' represents the moisture content, 'A' represents the ash content, and 'GCV' represents the gross calorific value.

Table 5. Grey relational grade values of moisture content, ash content and GCV values.

S. No.	Biomass fuel	NV			DS			GCV			GRG	RANK
		M	A	GCV	M	A	GCV	M	A	GCV		
1	Rubber wood	0.714	0.688	0.019	0.286	0.313	0.981	0.636	0.615	0.338	0.530	3
2	Eucalyptus wood	0.000	0.875	0.057	1.000	0.125	0.943	0.333	0.800	0.346	0.493	5
3	Mixed wood	0.571	1.000	0.000	0.429	0.000	1.000	0.539	1.000	0.333	0.624	2
4	Palm shell with fiber	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.333	1.000	0.778	1
5	Wood chips	0.071	0.875	0.038	0.929	0.125	0.962	0.350	0.800	0.342	0.497	4

From the grey relational analysis results presented in Table 5, it can be concluded that the palm shell with fiber is the efficient biomass fuel for boiler applications as compared to the remaining biomass fuels that are considered for the present study.

CONCLUSION

Biomass fuels being used for the boiler applications have been discussed in the present work. The important parameters to be studied for proposing a biomass fuel to a boiler application have been detailed. Five different biomass fuels have been considered for the present study such as rubber wood, eucalyptus wood, mixed wood (tamarind wood and neem wood), palm shell with fiber and wood chips (obtained from the *Prosopis juliflora* wood). The moisture content, ash content and gross calorific value (GCV) of the considered biomass fuels have been measured and reported. The economic analysis has been performed in which the feedstock cost and demand for the individual biomass fuels have been calculated and reported. Grey relational analysis has been performed to propose an optimal and efficient biomass fuel for the boiler application. From the GRA results, it was concluded that the palm shell with fiber (obtained grey relational grade = 0.778) is the efficient biomass fuel for boiler applications as compared to the remaining biomass fuels that are considered for the present study.

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