Use of pine needles for producing high-calorific value bio-briquettes and pine resin for biomass boiler

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ABSTRACT

Biomass, ranked as the fourth-largest energy source globally, presents a viable renewable energy option. However, inherent limitations such as low density and calorific value necessitate the development of quality-enhanced biomass, like biomass briquettes, for more efficient energy production. This study focuses on biomass briquette production using pine needles, abundant in the hilly regions of Sri Lanka, as a forestry waste-to-energy concept. The research aims to investigate the physicochemical properties of pine needles char for biomass briquette preparation and utilizing pine resin as a binding agent. Thermal degradation analysis, XRD tests, and physical property assessments were performed on raw materials and briquettes. The objectives include pine resin extraction and analysis of pine needles' properties, optimization of briquette composition to ensure high combustion efficiency and comparison of briquette properties with standards relevant to biomass. Results revealed that pine needle char possesses favorable characteristics for briquetting, with a moisture content of 6.105% and ash content of 4.233%. The 5:1 ratio briquette showed the best performance with a calorific value of 22.19 MJ/kg, a high density of 917.272 kg/m³, and a compression ratio of 3.507. Pine needle briquettes (PNB) were made with different ratio pine needles char and binder using a small-scale hydraulic press (2 tons; 5.5 MPa) with a honeycomb-type mold. The machine's estimated production capacity is 192 briquettes per day. The research results help to create inventive waste management solutions by transforming pine needles into valuable energy sources, benefiting the environment, industries, and self-employed individuals equally.

KEYWORDS: *Bio-Briquette, bio-char Calorific value, Pine Needle, Pine resin, Renewable energy,*

1 INTRODUCTION

Since the beginning of the 21st century, energy costs have been a significant percentage of the countries' production costs. In many countries, their main source of energy is fossil fuels. The use of fossil fuels is not sustainable as this is a non-renewable energy source (Sastry et al., 2013) In many developing countries, a substantial volume of agricultural residues is generated, yet their utilization is often inefficient, leading to significant environmental pollution. The primary residues include rice husks, sawdust, bagasse, corn husks, cotton stalks, and pine needles, which are abundant. Pine needles are traditionally regarded as forestry waste. Also, by 1983, there were 23,000 hectares of pine plantations in Sri Lanka, and currently, this area has expanded even further. As a result, pine needles and crop residues possess significant potential as valuable resources (Ruwanpathiranal et al., 2013)

In response to these challenges, the focus of this research shifts towards optimizing thermal efficiency and bulk density through the utilization of bio-briquetting techniques. The aim is to develop pine needle bio-briquettes, employing pine resin as a binder, thereby converting this abundant waste into

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a valuable resource. Conventional combustion methods yield low conversion efficiencies, often around 40%, and result in high particulate emissions exceeding 3000 mg/Nm³ in flue gases. Moreover, a significant portion of unburnt carbonaceous ash must be appropriately disposed of, with rice husk alone accounting for over 40% of the burnt feed. The briquette process, as a form of densification, not only enhances calorific value but also increases bulk density to levels as high as 600–800 kg/m³, compared to the typical 40–200 kg/m³ of loose biomass. (Pandey & Prasad Dhakal, 2013)

Biomass briquettes present an attractive alternative to traditional firewood, offering economic advantages and a reduced environmental footprint as a clean energy source. However, to fully realize their potential as a widespread fuel source, advancements in production technology are essential. The ideal briquette press should be cost-effective, user-friendly, and easily repairable. The present study seeks to investigate the physio-chemical properties, combustion characteristics, and emissions of Pine Needle Briquettes (PNBs). Through this analysis, the research aims to demonstrate PNBs' viability as an economical and eco-friendly solution to both waste management challenges and energy shortages, thereby contributing to sustainable development goals.

2. MATERIALS AND METHODS

The dry pine resin was collected from the Kandy Hill region of Sri Lanka. These samples underwent solar drying to reduce moisture content, following which proximate analysis was conducted to assess moisture, ash, and volatile content. The raw materials were then converted to char using the method suggested by Frederik Ronsse (Ronsse et al., 2013), followed by grinding to achieve a particle size smaller than 2mm The resin is heated until it liquefies, then mixed with pine needle char according to specified briquetting ratios. While warm, the mixture is filled into molds. Briquettes were formed using a hydraulic press briquetting machine, then sun-dried for several days to reduce moisture content further.

Figure 1 Hydraulic press Briquette Machine

Proximate analysis, encompassing moisture, ash, volatile matter, and fixed carbon content, was conducted alongside ultimate analysis (carbon, hydrogen, and oxygen) in a theoretical manner. The calorific value of the briquette samples was determined using practically and Aspen Plus simulation software. Performance analysis of the produced briquettes included testing for shutter index and density.

To understand the combustion characteristics, combustion tests were conducted, and ignition temperature was determined by igniting briquette samples at the base of a drought-free corner. The ignition time, recorded using a stopwatch, denoted the time required for the flame to ignite the briquette.

3. RESULTS AND DISCUSSION

In this study, PNBs were prepared and subjected to various physio-chemical tests. These briquettes serve industrial heating purposes and household needs, offering a clean-burning, carbon-neutral, and cost-effective fuel source. Figure 1 illustrates a PNB, cylindrical in shape, weighing approximately 200 grams. Unlike typical charcoal briquettes, PNBs feature vertical holes allowing for oxygen flow and controlled burning, resulting in a light blue flame. With a diameter of about 7.65cm, these briquettes burn for approximately 30-45 minutes. Furthermore, PNBs burn smokeless, which is a desirable characteristic for users. It is anticipated that these attributes will appeal to users, potentially prompting them to choose this fuel product over traditional charcoal and woody biomass.

Figure 2 Honeycomb type pine-biochar briqutte

Table 1 Physical Characteristics of the Briquette Samples

Parameters	**Pine Briquette**
Appearance	Black color, Cylindrical Shape with 5 holes
Average diameter	7.65cm
Average height	36mm
Weight	150g
Drying time	one day

3.1 Proximate Analysis

Moisture, volatile matter, and ash content were determined following the guidelines of (ASTM D 1762-84, 2011). Briefly, biochar samples weighing approximately 1g each were heated in duplicate in porcelain crucibles. The differences in sample weights before and after heating were recorded. For moisture content analysis, samples were dried at 105°C for 2 hours to achieve an oven-dry condition. Volatile matter content was assessed by heating samples to 950°C for 11 minutes with a covered crucible. Ash content determination involved heating samples to 750°C for a minimum of 2 hours with an uncovered crucible. A proximate analysis was conducted on the briquette to determine its carbon content and assess other key characteristics. This analysis provides valuable insights into moisture content, volatile matter, and ash content within the fuel cell. Understanding these attributes is crucial for evaluating the fuel's performance (Table 2). Moisture content has a negative effect on combustion efficiency (Kpalo et al., 2020), hence it is advisable to minimize moisture levels. Various factors need consideration before biomass can be deemed suitable for briquetting feedstock.

Table 2 proximate analysis of pine needle and pine needle char

Characteristics	**Pine Needle**	**Pine Needle Char**
Average Moisture Content (%)	19.27	3.21
Average Ash Content (%)	1.54	3.88
Average Volatile Matter Content (%)	79.01	68.7
Fixed Carbon Content (%)	19.46	27.42
Calorific value (MJ/kg)	18.97	20.45

Several considerations must be taken into account before biomass can be used as feedstock for briquetting. Apart from its abundant availability, specific characteristics must be met; notably, it should have low moisture content. In this study, the moisture content of pine needles was found to be 19.27% on a dry basis, falling within the acceptable range of 8-20% for briquette production. However, in most cases, the moisture limit for briquetting materials is up to 15%, although some materials with up to 20% moisture content can still be densified using a piston press. It is important to highlight that high moisture content exceeding 10% can cause difficulties in grinding and necessitate excessive energy for drying.

Biomass materials shouldn't be overly dried because excessive dryness can lead to friction, increasing energy requirements. Therefore, the ideal moisture content for the pine needles briquette is around 19.27%, which is suitable for this purpose. Biomass residues typically have lower ash content, except for rice husk which has 22.4% ash (Kuthe et al., 2021). However, their ashes contain a higher percentage of alkaline minerals, particularly potash. Pine needles had 1.54% ash content, while Pine needle charcoal had 3.88% ash content (Table 1), falling within the range of good quality charcoal (1.2% to 8.9%). Based on the present study, it was found that the ash content of pine needles and pine needles char (19.27%,3.21%%) is considerably lower than that of coal (33.47%). This difference in ash content may be attributed to the higher heating value of the briquettes.

Pine charcoal briquettes have a volatile matter content of 68.7%, higher than coal's 42.20%. The volatile matter in charcoal varies widely, typically ranging from over 40% to under 5%. In addition, the volatile matter of pine charcoal is 68.7% (Table 1), The high volatile matter content observed in the char derived from pine needles is attributed to the slow pyrolysis process conducted at 300 degrees Celsius for 3 hours. It is observed that at higher temperatures, the percentage of volatile matters decreases. High volatile charcoal is easier to ignite but may produce more smoke, whereas low volatile charcoal is harder to ignite but burns with less smoke. Therefore, high volatile charcoal is preferred for domestic use, while low-volatile charcoal is preferred for industrial applications. PNB demonstrates a high fixed carbon content of 27.42%, surpassing coal briquettes which contain only 18.59% carbon. Charcoal intended for domestic use should ideally contain 80.5% fixed carbon, while industrial charcoal should aim for 86.7%. Pine biomass, with a fixed carbon content of 27.42%, proves suitable for biomass briquette production. Controlling fixed carbon proportion can be achieved by adjusting maximum temperature and residence time during carbonization.(Gheorghe et al., 2009).

3.2 Ultimate analysis

The ultimate analysis of raw materials (pine needles) is a crucial aspect of understanding their chemical composition, which in turn informs their properties and potential applications. This analysis involves determining the elemental composition, including percentages of carbon, hydrogen, nitrogen, sulfur, and oxygen present. In the case of pine needles, the ultimate analysis reveals a composition of 48.35% carbon, 5.91% hydrogen, and 43.52% oxygen on a dry basis and pine needle char has a high fixed carbon than pine needles (27.74%) (Table 2).

Table 3 Ultimate analysis of pine needles and pine needles char

Sample	Fixed Carbon	Carbon(c)	Hydrogen(H)	Oxygen(O)
pine needles	19.36	47.831	5.843	43.022
pine needles char	27.74	49.1131	5.7381	41.4428

The calorific value stands as one of the most crucial attributes of fuel, representing the energy emitted per kilogram upon combustion. Pine needles have a calorific value of 19.6 MJ/kg, whereas pine needle char possesses a higher calorific value of 20.45 MJ/kg. Additionally, pine needle char exhibits a greater energy potential compared to pine needles, as well as other biomass materials such as Poplar, Sunflower husk, Rice straw, and Rice husk (Gravalos et al., 2016). This value serves as a key determinant in assessing the competitiveness of a processed fuel within a given market scenario. While factors like ease of handling and burning characteristics also influence market value, the calorific value holds paramount importance and warrants consideration when selecting raw material inputs. Moreover, there exists a significant relationship between calorific value and fixed carbon content. The correlation between these two factors demonstrates a highly favorable linear regression value (R^2) 0.9998 (nearing 1.000), approaching unity. so does the calorific value, indicating a strong correlation between fixed carbon content and calorific value (Anshariah et al., 2020)

3.2 TGA analysis

Thermogravimetric Analysis (TGA) is a technique used to monitor the weight changes of pine needles as they are heated. The thermal stability and decomposition of materials were determined using TA Instruments Trios. The TGA curve illustrates the percentage weight loss of pine needles at different temperature ranges. As can be seen from Figure 2, four distinct regions are identified (under O2 condition) initial weight loss due to moisture evaporation (32.13 °C to 105 °C), significant weight reduction from volatile organic compound decomposition (105 °C to 210 °C), slower decline from stable organic compound decomposition (210 °C to 315 °C), and sharp decrease from primary structure breakdown (315 °C to 420 °C). The TGA data aids in evaluating thermal stability and identifying pine needle components. Figures includes temperature (x-axis), weight percentage, and derivative weight (y-axis), with blue circles indicating data points and a vertical dashed line denoting maximum weight loss rate temperature.

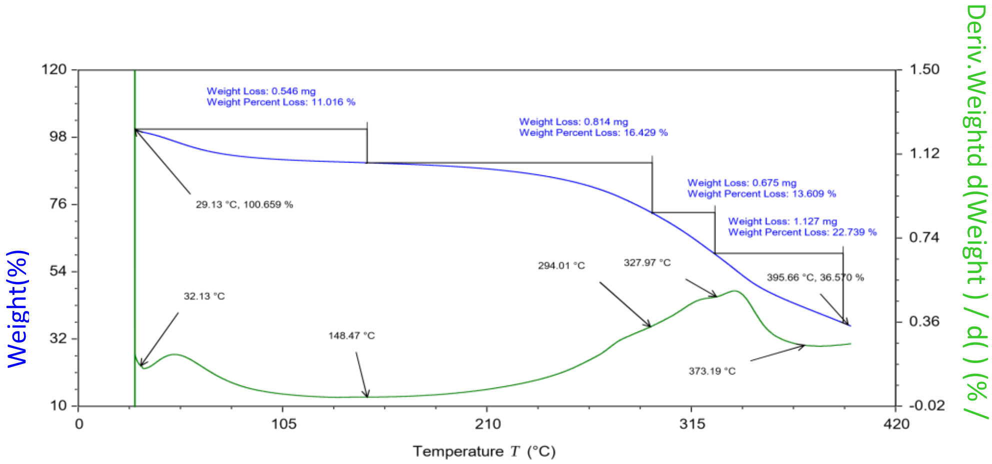

Figure 3 TGA of Pine Needles - Under O_2

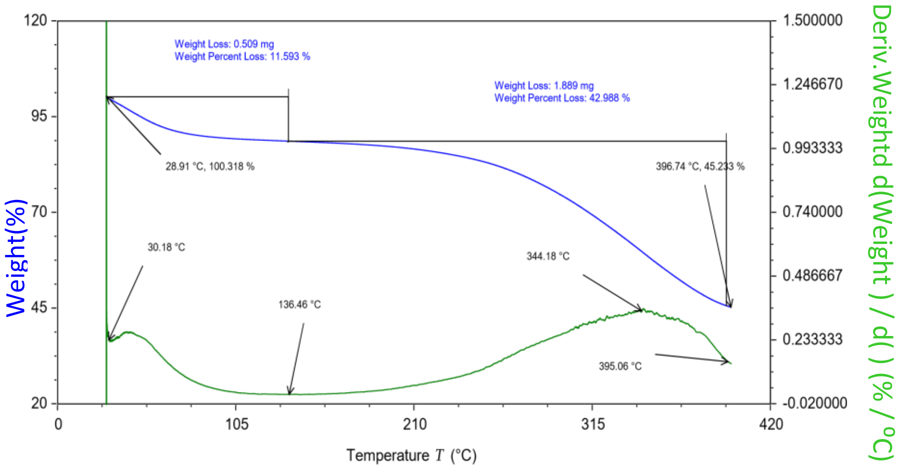

Figure 4 TGA of Pine Needles - Under N_2

The TGA analysis (under N_2 condition) according to the figure 3 indicates that weight loss initiates around 30°C due to moisture evaporation from the pine needles. Between 290°C and 370°C, a significant weight reduction occurs, likely as a result of organic material decomposition within the needles. This weight loss stabilizes around 370°C, indicating completion of decomposition for most volatile components within the pine needles.

3.4 Characteristic of briquettes

3.4.1 Moisture Content

The moisture content for the samples of 3:1, 4:1, and 5:1 was found to be 4.67%, 4.86%, and 5.04% respectively. The comparison of moisture content for all the samples.

$$Moisture\ content\ \% = \frac{W1-W2}{W1} \times 100\% \quad (1)$$

The lowest moisture content was observed in the 3:1 ratio sample due to its high resin content and relatively low pine char content, which only affected the moisture content of the char.

3.4.2 Ignition time

Ignition time for the briquette samples 3:1, 4:1, and 5:1 are 3.66 seconds, 4.33 seconds, and 12.19 seconds respectively. The highest ignition time, 12.19 seconds, is observed in the 5:1 sample. All samples exhibit very strong results in terms of ignition time. The main reason for this is the presence of pine resin and pine needle char, both of which contain very high volatile matter

3.4.3 Ignition temperature

The ignition temperature represents the lowest temperature required to start and sustain combustion in a substance when exposed to air. Pine needles, with an ignition temperature of 187.6, demonstrate better fuel properties compared to other biomass materials. Pine needles also exhibit a shorter ignition time. Ignition temperature decreases with higher volatile matter content in fuels and is influenced by factors such as particle size, sample dimensions, heating rate, and oxygen concentration.

Table 4 shatter Index with different binding agent ratio

Sample	Initial Weight (g)	After Weight (g)	Shatter Index	Shatter Resistance (%)
1 to 1	175.4105	170.1450	3.002	96.998
1 to 2	168.7750	167.8590	0.543	99.457
1 to 3	157.3250	156.5845	0.471	99.529
1 to 4	169.1305	168.7585	0.220	99.780

3.4.4 Shatter Index

The durability of the briquettes was assessed using the Shattered Index method outlined by (Method, 2000). Briquette samples were repeatedly dropped from a specific height of 1.5m (6 ft) onto a solid base. The fraction of the briquette remaining intact after each drop served as an indicator of its breakability.

The durability rating was expressed as a percentage of the initial mass of the material retained on the solid base. Four variations of pine needle briquettes, ranging from a ratio of 1:1 to 1:4, were tested using the formulas provided. These four variations exhibited superior shatter resistance compared to other briquettes, such as rice husk (72.4%) and groundnut shells (90.4%). (Tembe et al., 2014) In this experiment, four variations of briquettes were tested to determine the optimal binding ratio with respect to the shatter index. The 1:1 ratio exhibited more brittleness due to the higher concentration of pine resin (table 2), making it more inclined to breakage compared to the 1:4 ratio.

3.4.5 Approximate Calorific Value

The heating values, also known as the calorific value or energy value, of the pure and blended materials, were determined in the experiment. The results were 5005.34 cal/g, 4791.67 cal/g, and 5301.59 cal/g for the sample ratios of 3:1, 4:1, and 5:1, respectively. Hence, the sample with a 5:1 ratio has the highest calorific value of 5301.59 cal/g. The resin has an approximate calorific value of 31.8 MJ/kg.(Melapi et al., 2015).

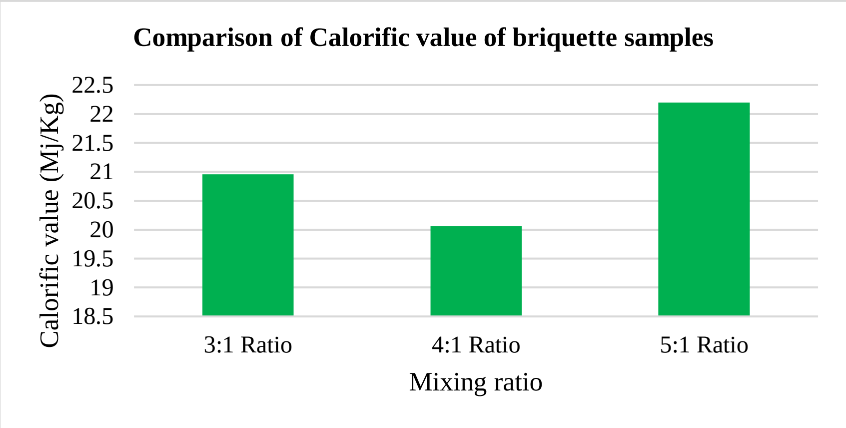

Figure 5 Comparison of Calorific value of briquette samples

3.4.6 Bulk Density

The bulk density of pine needles was found to be 261.53kg/m³, while pine needle char exhibited a higher bulk density of 360.12 kg/m³.

$$Bulk\ densty\ (g/cm^3) = \frac{Mass\ of\ raw\ material\ (g)}{Volume\ \ of\ container\ (cm^3)} \quad (2)$$

For the briquette samples, the bulk densities were 794.12kg/m³ for the 3:1 ratio, 866.31kg/m³ for the 4:1 ratio, and 917.27kg/m³ for the 5:1 ratio. Thus, the 5:1 briquette sample had the highest bulk density.

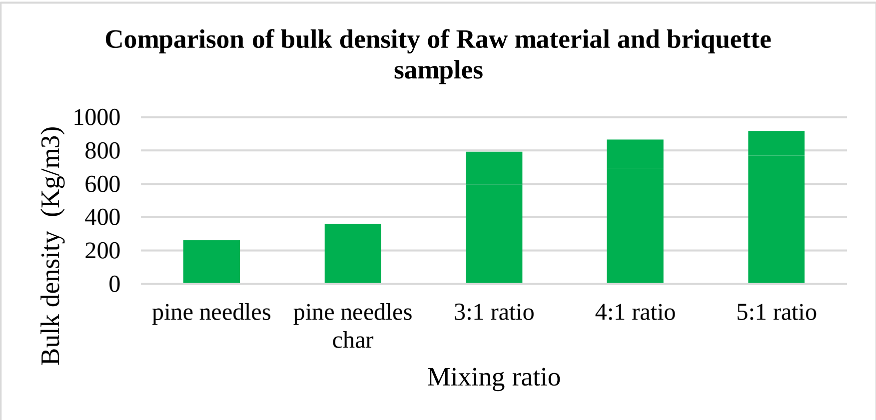

Figure 6 Comparison of bulk density of Raw material and briquette samples

3.4.7 Cost-Benefit Analysis

A cost-benefit analysis is essential for assessing the economic feasibility of briquette production. A small-scale briquetting machine was developed, producing 192 briquettes per day over an 8-hour period. The analysis includes initial costs (materials, laser cutting, assembly, installation, labor, and electricity) and operational costs (raw materials, energy, and maintenance). The unit cost was Rs 47.68 per kg, while market prices are Rs 25-30 per kg, requiring a reduction to Rs 12 per kg for competitiveness. To achieve this, production must increase to 591 briquettes per day, which can be accomplished by increasing the number of molds from one to four, raising daily production capacity from 30 kg to 85.55 kg.

4. CONCLUSION

The production and utilization of Pine Needle Briquettes (PNBs) offer a promising solution to energy and environmental challenges by transforming abundant pine needle waste into a valuable resource. This research optimized thermal efficiency and bulk density through bio-briquetting techniques. Proximate and ultimate analyses revealed favorable characteristics of PNBs, including low moisture content (4.67%) and high fixed carbon content (27.74%). Pine needle char has a calorific value of 20.45 MJ/kg, higher than pine needles and other biomass materials.

Briquettes with different ratios of pine needle char and pine resin were analyzed, showing calorific values of 5005.34 cal/g, 4791.67 cal/g, and 5301.59 cal/g for ratios 3:1, 4:1, and 5:1, respectively, with the 5:1 ratio performing best. Briquettes with pine resin as a binder had high calorific values (4791.67 cal/g to 5301.59 cal/g), appropriate moisture content (4.67% to 5.04%), high ignition times (3.6s to 12.1s), and high density (794.12 to 917.27 kg/m^3). These attributes make PNBs a viable alternative to traditional firewood, offering economic benefits and reduced environmental impact. PNBs exhibit clean-burning, smokeless combustion, and controlled burning due to vertical holes, making them suitable for industrial and household use.

The study advances sustainable waste management practices and addresses energy shortages, aligning with sustainable development goals. By harnessing pine needle waste to produce PNBs, the research enhances energy access, mitigates environmental pollution, and promotes socio-economic development. The cost-benefit analysis confirmed the economic viability of PNBs, which showed no fungal issues, unlike starch and water-mixed briquettes, enhancing their storage duration

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