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Experimental Evaluation of Torrefied Sawdust Pellets as a Potential Solid Fuel in Pakistan

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***Abstract* - This research paper assesses the effects of torrefaction on the fuel characteristics of sawdust pellets and evaluates their potential as an alternative solid fuel to coal in Pakistan. As an agrarian country, Pakistan generates significant quantities of biomass residues, including sawdust from furniture and carpentry industries, which are often underutilized or openly burned. In this work, sawdust collected from local carpentry workshops was pelletized using a laboratory-scale pellet machine with a 4 mm die configuration. The prepared pellets were torrefied at 200–220°C for 60 minutes. Moisture content, volatile matter, and ash content were determined through proximate and ultimate analyses, along with elemental composition analysis. The results indicate that torrefaction reduced volatile matter from 68.59% to 56.16% and increased carbon content from 39.37% to 63.15%. The higher heating value improved from 17.56 MJ/kg for non-torrefied pellets to 27.45 MJ/kg after torrefaction. The findings demonstrate that torrefaction enhances the energy density and fuel characteristics of sawdust pellets, making them more comparable to coal for thermal energy applications. These results suggest that torrefied sawdust pellets have strong potential as a partial substitute for coal in Pakistan's energy sector.**
***Keywords:* Biomass, Thermochemical Treatment, Torrefaction, Palletization, Biofuel**

I. INTRODUCTION

The increasing population and industrialization of the world have led to a rise in energy demand [1, 2]. This has forced us to rely heavily on fossil fuels to meet our energy needs [3]. The combustion of coal, crude oil, and natural gas results in the intensive production of pollutants, which are increasingly being restricted due to growing environmental regulations [4, 5]. Climate change is now considered a serious threat to living beings by leading scientists [6].

Current global energy studies are focused on reducing energy consumption and carbon dioxide emissions and demonstrate a strong commitment to green and sustainable energy sources [7]. There is an urgent need to shift toward the utilization of green energy that safeguards the health of both humans and the environment [8–10]. Solar, wind, hydro, and biomass are renewable sources of energy that are considered relatively pollution-free [11].

These are sources that are naturally replenished and can generate power at an almost infinite level. In a world that is becoming cleaner by adopting renewable energy to manage greenhouse gas emissionsand combat climate change, continuous technological development is still needed. Despite environmental and location-related challenges, efficiency and reliability can be improved through ongoing research and the adoption of diverse renewable energy sources [13].

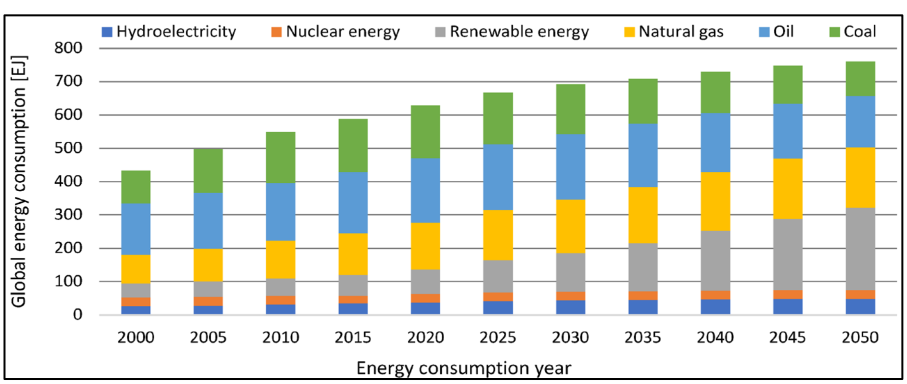

Fig.1 Energy Consumption 2000-2050 on a Global Level [12]

A. Biomass energy

The current high energy consumption rates across the world have led to the need to explore alternative energy sources to curb overreliance on traditional sources of energy [14], as illustrated in Figure 2. Biomass is a combination of the words *bio* and *mass*. It is derived from plant and animal sources such as algae, trees, and crops and consists of organic matter produced through photosynthesis. It includes both terrestrial and aquatic vegetation, as well as natural waste. When burned, the chemical energy stored in biomass is converted into mechanical and subsequently electrical energy [15].

Biomass has become a key focus in global energy policy discussions, particularly within the European Union, which has integrated environmental protection and sustainability into its strategic development goals. As a renewable energy source, biomass holds significant potential for producing biofuels, electricity, and heat [16]. Biomass contributes about 9% of global energy consumption and 35% in developing countries; however, realizing its full potential requires reducing the high transportation costs associated with agricultural residues [17].

The International Energy Agency (IEA) reports that biofuels have the potential to supply nearly 27% of global transportation fuel demand by 2050. Currently, the share of renewable energy sources worldwide is estimated at 18%, including biomass, hydropower, wind, and solar energy [10]. Naqvi, Salman Raza, et al. [18] reported that biomass energy is mainly derived from biodiesel (68%), followed by charcoal (10%), black liquor (7%), ethanol (4%), municipal waste (3%), wood fuel (2%), forestry by-products (2%), industrial residues (1%), and wood pellets (1%), as illustrated below.

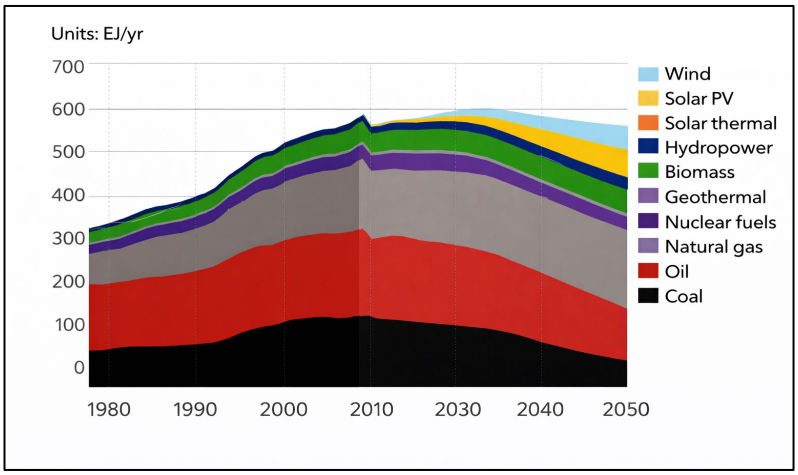

Fig.2 Energy Consumption in the World Between 1980 and 2050 (Adopted: IEA 2019)

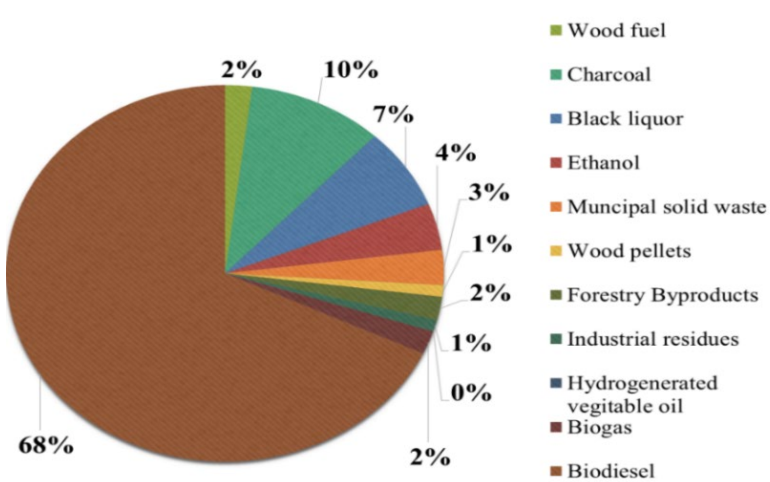

Fig.3 Various Origin of Biomass and their Utilization [18]

The utilization of biomass as a source of energy also refers to the waste-to-energy concept, which helps address environmental pollution and reduce landfilling issues [19]. As demonstrated by Tursi, Antonio, biomass is an entirely renewable energy source because the CO_2 emitted during its combustion does not increase atmospheric carbon dioxide levels, as it is biogenic. In other words, plants absorb the CO_2 released from the decay of organic materials to grow and carry out their metabolic activities. Consequently, the use of biomass merely accelerates the natural carbon cycle, allowing the CO_2 released into the atmosphere to be reabsorbed by plants for the regeneration of new biomass [16], as shown in Figure 4.

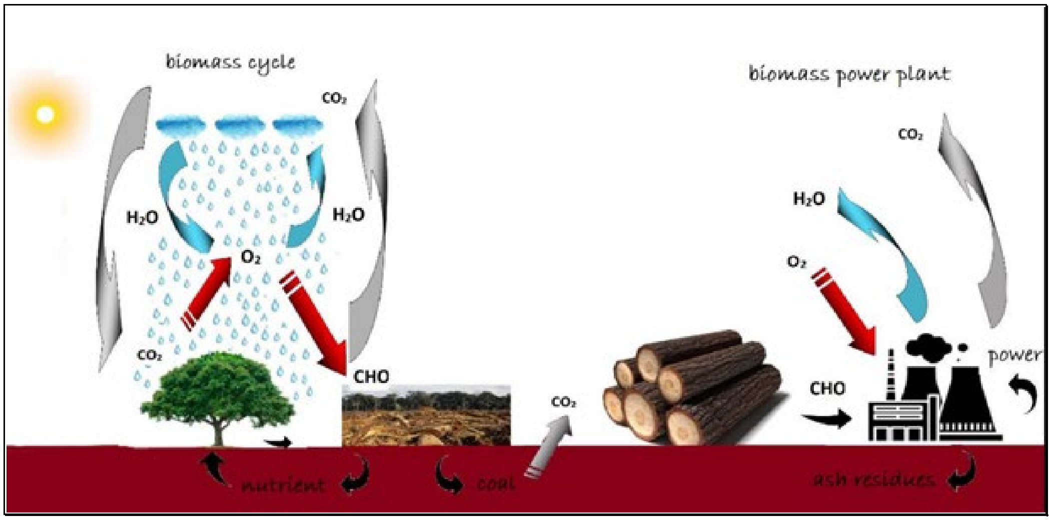

Fig.4 Biomass Energy Cycle [20]

B. Sources of Biomass

Biomass occurs in natural forms, and its utilization is important because it can significantly reduce reliance on non-renewable energy sources [21]. P. Ning et al. highlighted that plant biomass, derived mainly from forests, crops, and agricultural residues, represents the most abundant source of renewable energy. It primarily consists of wood, crop residues, and dedicated energy crops used for fuel production and energy generation. Chemically, it is composed of approximately 42–47% carbon, 40–44% oxygen, and slightly more than 6% hydrogen (on a dry basis). Overall, plant biomass serves as a versatile resource for producing various high-value energy and material products [22].

Biomass can be mainly divided into three distinct categories: solid (woody and non-woody biomass), liquid (generated after processing waste), and gaseous (generated after fuel processing) [23]. B. Dukhnytskyi categorized biomass according to its source and physical condition, as shown in Table I. Beyond physical state, biomass can also be categorized based on its chemical composition, as compositional characteristics determine energy content, conversion potential, and processing suitability. Composition influences key properties such as calorific value and adaptability to bioprocessing technologies. Moreover, compositional analysis reveals opportunities for the transformation of biomass into high-grade fuels, chemicals, and materials. The composition of biomass provides a fundamental basis for its classification [25].

TABLE I THE CLASSIFICATION OF BIOMASS IS ROOTED IN ITS ORIGINAL STATE AND SOURCE [24]

Processed waste (PW)	**Processed fuels (PF)**	**Non-woody biomass (NWB)**	**Woody biomass (WB)**
Wastes of Sawmill	Charcoal (wood and residues)	(Sugarcane) energy crops	Shrubs
Plant oil cake	Briquette and densified biomass	Straws	Trees
Fruits waste	Biogas	Tobacco, cassava,cotton	Bushes (coffee and tea)
Nutshells and flesh	Palm and sunflower plant oil	Grasses	Forest floor sweepings
Bagasse	Producer gas	Banana	In Palms
Cereal husk	Methanol and Ethanol	Soft plant stems	Bamboo.

1. *Cellulosic biomass:* A common form of plant material mostly consisting of structural cellulose, generally containing more than 25% cellulose, such as agricultural residues [26].
2. *Starch biomass:* Feedstocks in which starch is the major carbohydrate (over 20%), such as grains and corn kernels [27].
3. *Lignocellulosic biomass:* Materials containing more than 10% lignin along with cellulose and hemicellulose.

The majority of biomass materials, such as wood and inedible plant biomass (e.g., grasses and forest thinnings), fall into this category [28].

4. *Lipid biomass:* Feedstocks that contain more than 20% fats or oils as energy carriers. Examples include microalgae (e.g., *Chlorella*) and oilseeds [29].
5. *Protein biomass:* Biomass containing around 20% protein, such as soybeans [30].
6. *Waste biomass:* Municipal solid waste and industrial effluents comprising diverse mixtures of carbohydrates, fats, and lignin without a single dominant component [31]. Examples include food waste and refinery residues.

TABLE II DIFFERENT FORMS OF BIOMASS

Biomass Type	Key Observations	Reported by
Cellulosic biomass	Primarily cellulose-rich plant residues (>25% cellulose)	M. A. d. Souza *et al.,* 2022 [26]
Starch biomass	Feedstocks contain >20% starch as main carbohydrate	L. J. Falarz *et al.,* 2018 [27]
Lignocellulosic biomass	Contains >10% lignin with cellulose and hemicellulose	A. Sahoo et al., 2022 [28]
Lipid biomass	High fat/oil content (>20%) as primary energy carrier	A. Khanal & A. Shah, 2021 [29]
Protein biomass	High protein content (>20%)	L. Du *et al.,* 2020 [30]
Carbon-rich waste biomass	Mixed municipal and industrial residues with no dominant component	A. Thakur *et al.,* 2024 [31]

It is important to note that these classifications represent more of a continuum than strict divisions. Biomass feedstocks tend to have overlapping compositional profiles; for example, tree tissues range from cellulose-rich bark to lignin-dense wood, highlighting the natural variability of biomass resources [32].

Wood waste is recognized as a significant environmental threat due to the shortage of landfills and related environmental issues, particularly in emerging nations, where its accumulation from mills, industries, and household activities is increasing annually [33]. Some wastes originate from various forms of farming and are referred to as biomass waste. Agricultural wastes include crop residues such as rice husks, spoiled or low-quality fruits and vegetables, maize cobs, and wheat straw. Field and process residues are the two main types produced. Branches, grains, stalks, and leaves discarded in fields are often not cleared after harvesting. In contrast, residues generated after crop processing include roots, peels, stubble, pulp, shells, stalks, straw, stems, leaves, seeds, bagasse, husks, molasses, and other processing by-products produced annually [34].

Several researchers have studied sawdust and concluded that effective waste management can help convert the more than 1.5 million tons of sawdust waste that are burned or disposed of improperly each year into value-added products [35]. In various industries, including energy and agriculture, sawdust-a timber-industry waste that contributes to environmental pollution-can be transformed into a valuable resource [36]. It can be used to produce sawdust-based building composites that meet international standards for strength, water absorption, and modulus of elasticity. These composites include sawdust blocks made with concrete or bricks, particleboards, and sawdust concrete [37]. The demand for wood pellets in industrial applications has expanded rapidly because they reduce costs while minimizing environmental pollution. Compacted sawdust and wood waste are converted into pellets that can replace nonrenewable fossil fuels, such as coal, for cleaner energy production [38].

Biomass conversion technologies refer to the scientific and engineering processes used to convert raw biomass into usable energy products such as heat, electricity, and biofuels. These technologies operate through three major pathways: thermochemical, biochemical, and chemical conversion [39]. L. C. Sá *et al.* stated that each biomass conversion pathway comprises several specialized techniques designed to improve efficiency, enhance fuel quality, and minimize environmental emissions, as depicted in Figure 5.

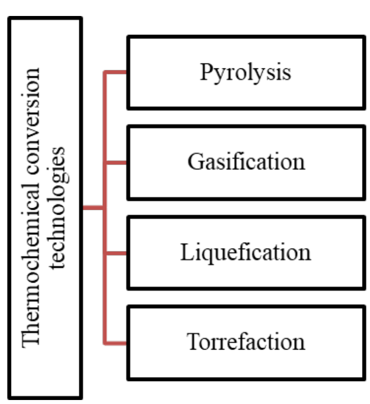

Fig.5 Biomass Conversion Technologies [40]

This process addresses waste management and plays a vital role in advancing sustainability. The following sections elucidate the various forms of biomass utilized, their inherent characteristics, and the advantages associated with the pelletization process. Pelletization densifies these materials, enhancing their energy density, handling characteristics, and combustibility, thereby making them an efficient and eco-friendly fuel alternative. Thermochemical conversion does not necessarily produce useful energy directly; however, the initial biomass fuel is transformed into more practical transportation energy carriers, including synthesis gas, oils, or methanol, under controlled temperature and oxygen conditions [41].

A pretreatment process is conducted in an inert or oxygen-free atmosphere, where biomass is processed at temperatures between 200 and 300°C. This process transforms raw biomass into "torrefied biomass," a carbon-rich solid [42]. Torrefaction is also referred to as wood baking, mild or slow pyrolysis, biomass carbonization, roasting, or high-temperature drying [43]. Torrefaction results in higher C/O and C/H ratios, improved ignition properties, reduced moisture content, increased energy density, enhanced grindability, and decreased energy requirements for grinding. It also produces hydrophobic biomass, meaning biomass with a lower affinity for water [44].

Wood biomass processed in furniture and related industries generates sawdust as waste. This waste is available in large quantities but has not been properly utilized for energy applications. This research aims to utilize sawdust waste to produce wood pellets and apply biomass conversion technology, specifically torrefaction, to evaluate the characteristics of pelletized biomass. Proximate and ultimate analyses are used to determine the biomass characteristics.

II. MATERIALS AND METHODOLOGY

A. Sample Preparation (Biomass Waste Collection)

Sawdust was collected from local carpentry workshops in Khairpur, Pakistan. The collected biomass consisted of mixed wood residues generated from furniture manufacturing processes. The material was air-dried and screened to remove large impurities before further processing.

B. Pellet Preparation

The prepared sawdust was converted into pellets using a laboratory-scale pellet machine equipped with a 4 mm die, as shown in Figure 6. A small amount of moisture was added to facilitate pellet formation. The pelletization process produced cylindrical pellets with a uniform diameter suitable for further thermal treatment. The produced pellets were stored in airtight containers before undergoing torrefaction.

(a) (b)

Fig.6 Palletization of Sawdust (A) Before Palletization and (B) After Palletization

C. Torrefaction Procedure

Torrefaction experiments were conducted in a laboratory oven under controlled conditions. Approximately 50 g of pellets were placed in the reactor and heated within the temperature range of 200–220°C for 60 minutes. Immediately after torrefaction, the samples were allowed to cool to room temperature and were then stored for characterization.

Fig.7 Steps Used in Torrefaction

D. Characterization

The properties of torrefied and non-torrefied biomass delineate their performance and suitability for various applications. Torrefied pellets are more brittle and less elastic than non-torrefied pellets. They exhibit better grindability and improved stability during storage and transport. Non-torrefied pellets, however, are more suitable for applications with lower energy density requirements. The properties of the torrefied and non-torrefied pellets were determined through proximate and ultimate analyses. At the initial stage, 10 g samples of both torrefied and non-torrefied biomass were prepared. Subsequently, following the ASME Standard 7582-15 guidelines, proximate analysis (Model LECO TGA 701) and ultimate analysis (Model LECO CHNO TruSpec Micro Analyzer) were conducted. The gross calorific value (GCV) was calculated using Equation 1 [45].

$$GCV\ (MJ/Kg) = 37.777 - 0.647M - 0.387A - 0.089VMR2 \qquad (1)$$

Where; M = the moisture content, A = the ash content and VM = the volatile matter.

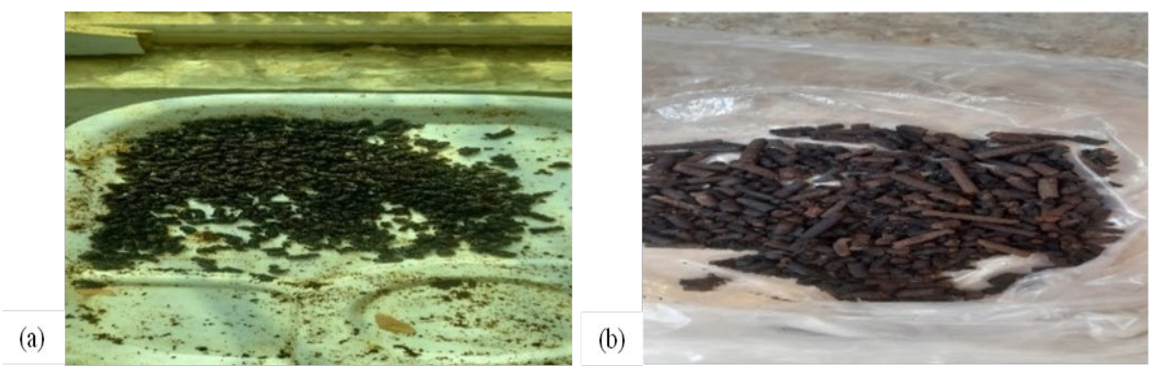

Fig.8 Sawdust Pellets (A) Non-Torrefied and (B) Torrefied

III. RESULTS AND DISCUSSION

In this study, the utilization of wood biomass waste produced at various stages of furniture making, including cutting, processing, and polishing, has been considered. Studies have revealed that a considerable amount of wood waste in the form of sawdust generated from processed wood is available but is not used efficiently; instead, it is either dispersed into the open environment or burned inefficiently. This practice degrades the landscape and creates environmental problems due to open burning. The present study aims to utilize this sawdust waste for useful energy generation by producing pellets and enhancing its low-grade efficiency to make it suitable for different applications.

In a study on prevalent agricultural biomass waste, research was carried out on the crop yield-to-residue ratio, energy potential accessibility factor, total availability time, and available quantity [46]. The total amount of waste agricultural biomass produced was 2533 kt/y. Agricultural biomass waste may be utilized as a source of industrial as well as residential energy. The theoretical methane potential for crop waste biomass in District Sanghar was determined to be 535,976 kt/y [47]. This could contribute to climate change mitigation and sustainable development by meeting 14% of the nation's energy demand, with a potential of 3050 kWh/ton [48]. In particular, rice straw and rice husk total 10,147.65 thousand tons. These residues can be used to generate alternative energy, with an estimated theoretical energy potential of 159,219 TJ, thereby reducing reliance on fossil fuels. Pakistan specifically produces 10,147.65 thousand tons of rice husk and straw, which can serve as alternative energy sources and reduce dependence on fossil fuels [49]. Such crop residues produced in Pakistan have strong potential to be utilized as alternative energy sources to lessen reliance on fossil fuels, address the demand–supply imbalance, and mitigate the impacts of global warming. Figure 9 presents the proximate analysis of wood pellets, both torrefied and non-torrefied. The moisture content of the torrefied pellets is 6.1%, while that of the non-torrefied pellets is 6.39%. The volatile matter content of non-torrefied and torrefied biomass is 68.59% and 56.16%, respectively. In terms of ash content, torrefied wood pellets contain 11.47%, whereas non-torrefied wood pellets contain 7.7%. The lower moisture content and volatile matter, along with the higher ash content of torrefied biomass, are attributable to the torrefaction process compared with non-torrefied biomass.

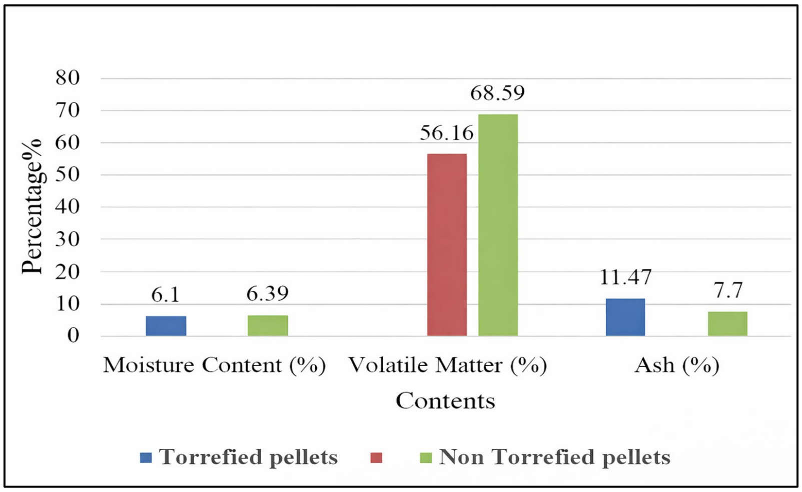

Fig.9 Comparison of Proximate Analysis of Torrefied and Non-Torrefied Pellets

The ultimate analysis of torrefied and non-torrefied wood pellets is shown in Figure 10. Torrefied wood pellets contain 63.15% carbon, whereas non-torrefied wood pellets contain 39.37%. The higher carbon content in torrefied biomass is due to the devolatilization that occurs during the torrefaction process. The hydrogen content is 4.25% in torrefied pellets and 6.03% in non-torrefied wood pellets. The nitrogen content is 0.73% in torrefied wood pellets and 0.43% in non-torrefied wood pellets. The oxygen content is 23.14% in torrefied wood pellets and 43.52% in non-torrefied wood pellets. These values provide a better understanding of the elemental composition of wood waste. The lower contents of H, N, and O in torrefied biomass compared to non-torrefied biomass indicate the higher potential energy characteristics of torrefied biomass.

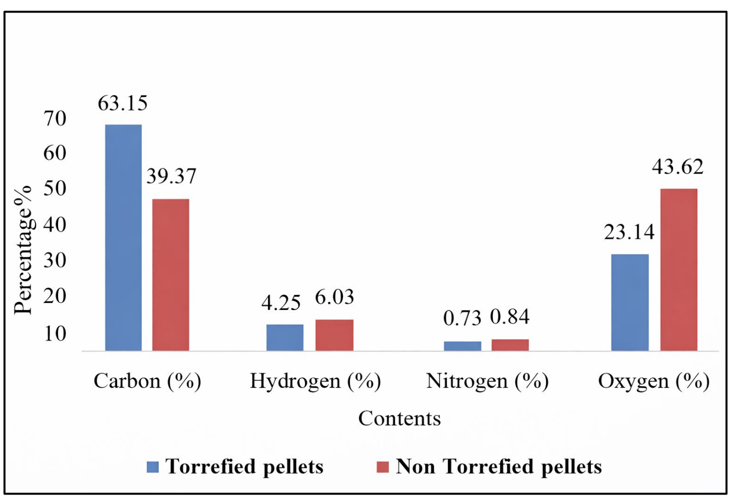

Fig.10 Ultimate Analysis of Torrefied and Non-Torrefied Pellets

The calorific value of biomass indicates the amount of energy potential in the waste. The calorific values of torrefied and non-torrefied biomass are shown in Figure 8. Equation 1 was used to determine the heating value of the biomass. Based on Figure 11, it is evident that the heating (calorific) value of torrefied biomass is significantly higher compared to non-torrefied biomass. It is important to note that the calorific value of biomass waste increases substantially when the torrefaction process is applied, compared to non-torrefied biomass waste.

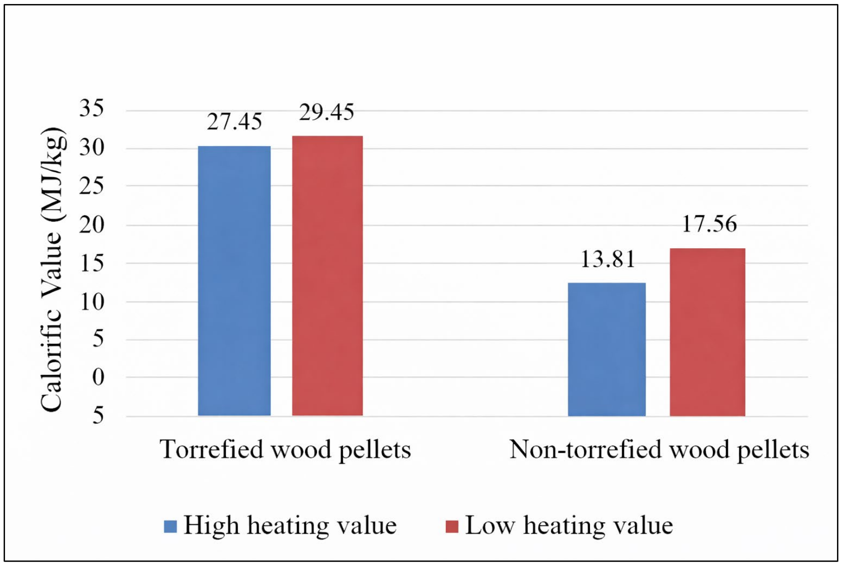

Fig.11 Calorific Value Comparison of Torrefied and Non-Torrefied Wood Pellets

Coal, non-torrefied wood pellets, and torrefied wood pellets were examined in terms of their applicability as alternative solid fuels. Torrefied pellets showed lower moisture content and volatile matter than non-torrefied pellets, leading to enhanced combustion and energy performance. Due to the torrefaction process, torrefied pellets also demonstrated improved grindability and hydrophobic characteristics, which enhance storage stability and handling properties. Figure 12 shows that the moisture content of torrefied pellets (3.3%) was lower than that of non-torrefied pellets (4.5%) and was comparable to coal (3.94%). The volatile matter content decreased from 72.53% in non-torrefied pellets to 47.83% after torrefaction, while coal exhibited 38.34%. Ash content values were 2.31%, 5.61%, and 7.31% for torrefied pellets, non-torrefied pellets, and coal, respectively. The fixed carbon content increased from 12.28% in non-torrefied pellets to 32.23% in torrefied pellets, whereas coal showed the highest value at 68.32%. The ultimate analysis showed that the carbon content was higher after torrefaction (63.15%) than in non-torrefied pellets (39.37%), approaching that of coal (75.62%). Hydrogen and nitrogen contents were lower in torrefied pellets compared to non-torrefied biomass, while the oxygen content decreased from 43.62% to 23.14% after torrefaction. The calorific value of the torrefied pellets was significantly higher than that of the non-torrefied pellets but remained lower than that of coal. Overall, torrefied wood pellets demonstrate improved fuel characteristics compared to untreated biomass and exhibit properties closer to coal. Although coal still possesses a higher energy density, torrefied pellets present a promising and comparatively cleaner alternative for thermal energy applications.

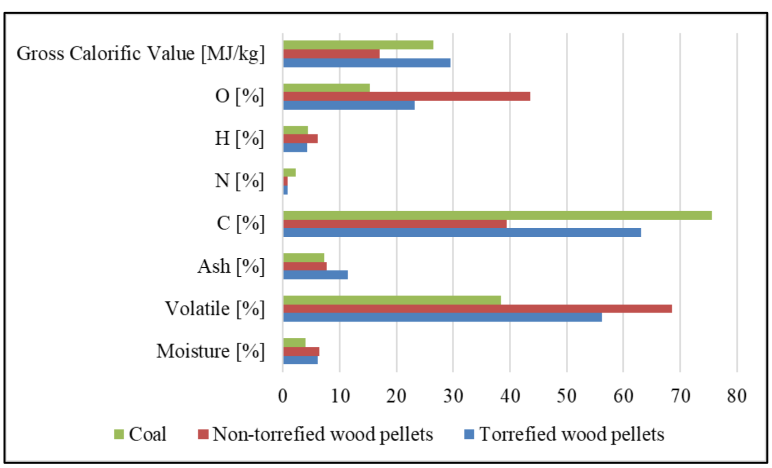

Fig.12 Torrefied and Non-Torrefied Pellets Characteristics Comparison with Coal

IV. CONCLUSION

Wood biomass waste produced at various stages of furniture making, including cutting, processing, and polishing, has not been utilized efficiently. Therefore, the present study aims to convert this sawdust waste into useful energy by producing pellets and enhancing its low-grade efficiency to make it suitable for different applications. Proximate and ultimate analyses were used to determine the characteristics of the non-torrefied biomass waste. Biomass torrefaction conversion technology was applied to obtain torrefied biomass. Finally, the properties of torrefied and non-torrefied biomass waste were compared with coal. The study concludes that wood waste (in the form of sawdust) generated from processed furniture and related applications can be utilized for energy production. Proximate and ultimate analyses demonstrated that the application of torrefaction technology significantly improved the properties of the biomass waste. The calorific value of torrefied biomass was enhanced by 56% compared to non-torrefied biomass. Moreover, the study reveals that torrefied wood pellets are more efficient than untreated biomass and are nearly comparable to coal in terms of energy density and fixed carbon content. Although coal has a slight advantage in calorific value, torrefied pellets represent a more favorable and lower-emission alternative, particularly where clean energy and reduced carbon emissions are primary concerns.

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