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Characteristics of Agricultural and Plantation Wastes as Solid Biomass Energy Feedstock: A Systematic Review

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Abstract

The conversion of agricultural and plantation waste into biomass energy represents a promising pathway in the global transition to environmentally friendly energy sources. However, systematic comparisons of different types of agricultural and plantation biomass waste remain limited. This study aims to identify and evaluate the characteristics of various agricultural and plantation wastes to determine their feasibility as solid biomass energy feedstock. A systematic literature review was conducted using databases such as PubMed, DOAJ, and manual searches, focusing on articles published between 2014 and 2025. A total of 32 relevant studies were selected based on inclusion criteria. The analysis revealed that coconut shells, coffee grounds, and oil palm kernel shells possess superior fuel properties, particularly high calorific values of ≥ 4000 cal/g, making them highly suitable for solid biofuel production. These findings emphasize the strategic potential of agricultural and plantation waste as a sustainable energy source. The study contributes to the advancement of circular economy practices, promotes effective waste management, and supports the achievement of Sustainable Development Goals (SDGs).

Keywords: renewable energy; properties; sustainability; environment; circular economy.

1. Introduction

Total primary energy consumption rose by 2% compared to 2022. This level is 0.6% higher than the average over the past decade and exceeds the 2019 pre-pandemic level by more than 5%. Renewable sources contributed 14.6% to the total primary energy use, reflecting a 0.4% growth from the previous year. On the other hand, fossil fuels' contribution to primary energy consumption dropped by 0.4%, amounting to 81.5%. This indicates a global shift toward the utilization of renewable energy as a substitute for fossil fuels. For decades, fossil energy sources have been the primary reliance; however, their availability is limited. In addition, their use has led to serious environmental consequences, such as carbon emissions that contribute significantly to global warming [1].

Renewable energy is considered a vital alternative to lessen reliance on fossil fuels and support environmental conservation efforts. Biomass-based energy is one of renewable energy forms that is environmentally friendly. Recognized worldwide as a sustainable energy resource, biomass currently ranks as the fourth most widely used energy source globally—following coal, oil, and natural gas—contributing approximately 10.2% or about 50.3 exajoules annually to the global primary energy supply [2].

Indonesia, as a country rich in biological resources, holds significant potential for developing renewable energy derived from waste. Biomass waste from the agricultural and plantation sectors is abundantly available across the country, yet remains underutilized [3]. This type of waste holds considerable promise as a sustainable, economical, renewable, and environmentally friendly alternative energy source. Nevertheless, due to certain limitations, such as its tendency to absorb and release moisture easily, high water content, and low calorific value, biomass must firstly undergo processing, including grinding or drying, to improve its suitability for energy production [4].

Utilizing these wastes as solid biofuels, such as wood pellets, wood briquettes, and charcoal briquettes, is an innovative step to increase the economic value of agricultural and plantation wastes while supporting climate

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change mitigation. This does not only contribute to energy diversification but also support the achievement of SDGs (Sustainable Development Goals). In the attempt to support Affordable and Clean Energy (SDG 7) through the promotion of renewable energy development and contribute to Responsible Consumption and Production (SDG 12), we can start with implementing sustainable waste management practices and increased waste valorization, and Action on Climate Change (SDG 13) through the reduction of carbon emissions and the production of carbon neutral energy.

On the other hand, the energy quality of biomass waste differs across types. Factors such as moisture content, ash levels, volatile components, fixed carbon, and calorific value significantly influence the potential and efficiency of biomass as a fuel source. In developing countries, where economies heavily rely on natural resources, particularly agriculture and plantations, the use of biomass for high-energy applications is especially relevant. Still, utilizing biomass waste directly as fuel poses certain challenges, such as elevated moisture levels and low energy density, which lead to issues in conversion technologies and additional costs for transportation, handling, and grinding [5]. Therefore, it is essential to conduct an in-depth literature review on the characteristics of various agricultural and plantation wastes to assess their feasibility as raw materials for solid biomass energy. In this study, the term "solid biofuel" refers to fuels derived from biomass in solid form, including waste, with a variety of uses, particularly for domestic cooking and heating [6], [7]. Pellets are solid biomass-based fuel type with a smaller size than briquettes which are usually produced under high pressure with or without a binder [8]–[10]. Meanwhile, briquettes are larger solid fuels and formed similarly by compressing biomass waste under high pressure, producing a dense and uniform product [11]–[13].

2. Experimental Methods

A comprehensive literature search was conducted using the PubMed and DOAJ databases, employing the keywords ("agricultural waste" OR "crop residue" OR "plantation waste") AND ("solid biofuel" OR "pellet" OR "briquette" OR "charcoal" OR "charcoal briquettes"). In addition, to obtain supplementary data, the authors also performed a manual literature search. The scope of the literature was limited to articles published between 2014 and 2025. Inclusion criteria included research or peer-reviewed articles; studies that provided data on the physicochemical and thermal characteristics of agricultural and plantation biomass for solid biofuel production; and publications in English or Indonesian. Exclusion criteria included non-full-text materials (e.g., abstracts); articles that focused only on non-solid biofuels (e.g., biogas, bioethanol), and studies that lacked relevant biomass characterization.

The search using the criteria above identified several relevant articles: PubMed (n = 53), DOAJ (n = 14), and 41 additional articles identified through manual searching. After reviewing the titles, abstracts, and full content to assess their relevance to agricultural and plantation wastes used as raw materials for solid biofuel production, 54 articles were selected and included in this literature review, as illustrated in Figure 1. For each selected study, parameters in assessing the potential of waste for solid biofuel applications were extracted and presented in Table 1.

Table 1. Biomass Selection Characteristic Parameters

Parameter	Description
Biomass type	Wastes of specific agricultural and plantation origin evaluated in the study [14]
Moisture content (%)	The percentage of water content in the biomass [15]
Ash content (%)	Inorganic residue left after combustion [6]
Volatile matter (%)	Compounds that vaporize when the biomass is heated [16]
Fixed carbon (%)	The solid carbon fraction remaining after volatile matter is released [17]
Calorific value (cal/g)	The energy content or heating value of biomass; a key indicator of fuel quality [18]
Lignin content (%)	Chemical components that play an important role in strength and energy content [19]
Cellulose content (%)	Chemical components that affect calorific value and combustion efficiency [20]
Hemicellulose content (%)	Chemical components that affect volatile matter and ignition characteristics [21]

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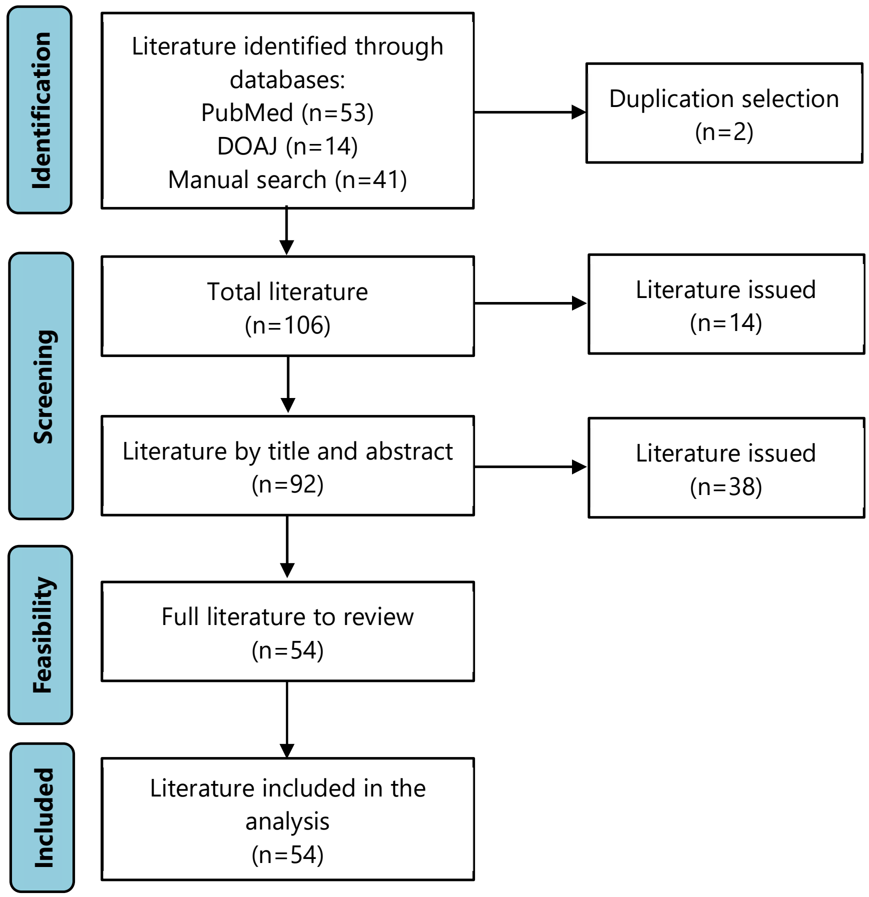

Figure 1. Prisma flowchart

3. Results and Discussion

3.1. Solid Biofuel Quality Parameters

The feasibility of biomass as a raw material for solid biofuel is determined by several essential quality parameters. These parameters are critical to ensure its performance and suitability as an alternative energy source. The main indicators encompass physical characteristics (such as moisture content), mechanical properties, chemical components (including ash percentage, volatile compound, and fixed carbon), as well as thermal properties (like calorific value). A thorough understanding of these parameters is fundamental for evaluating the overall quality and efficiency of solid biofuels.

3.1.1 Moisture Content

High water content has a negative impact on solid biofuels due to difficulties in ignition/burning, resulting in a longer time required for fuel combustion. In addition, the calorific value of the fuel decreases due to the energy consumption for water vaporization [22], [23]. Therefore, if biomass raw materials from agricultural and plantation waste have a high water content, drying must be carried out and storage conditions must be ensured properly so that the water content is not reabsorbed after drying [24], [25].

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3.1.2 Ash Content

Low ash content is an essential requirement for solid biofuels. Solid biofuels with low ash levels tend to produce more efficient heat compared to those with high ash content. On the other hand, elevated ash content results in higher particulate emissions and reduces combustion efficiency when used in stoves, furnaces, and gasifiers [26].

3.1.3 Volatile Matter

Volatile matter represents the carbon, hydrogen, and oxygen components present in solid biofuels that are converted into vapor when heated. Generally, a higher percentage of volatile matter indicates a higher combustion rate. The higher the volatile content, the more easily wood briquettes ignite and burn, while producing significant smoke upon ignition [27].

3.1.4 Fixed Carbon

Fixed carbon refers to the portion of solid fuel that remains combustible after the volatile substances have been eliminated. It plays a significant role in influencing the calorific value — higher fixed carbon typically results in greater energy yield. Solid biofuels with elevated fixed carbon levels have generally higher quality, as they emit less smoke when burned. In contrast, lower fixed carbon content often indicates inferior fuel quality. The amount of fixed carbon in solid biofuels is affected by both ash and volatile matter content. Fuels with high fixed carbon tend to exhibit lower levels of ash and volatile substances. Overall, fixed carbon is a critical factor in assessing the energy potential of solid biofuels. [4], [28].

3.1.5 Calorific Value

The primary quality parameter of solid biofuel is its calorific value, which plays a crucial role in determining fuel efficiency. Calorific value, or energy content, indicates the amount of heat produced during combustion. It is influenced by various factors such as moisture level, volatile substances, ash content, and the amount of fixed carbon. Higher levels of ash and moisture reduce the calorific value, while a greater amount of fixed carbon contributes to a higher calorific value and results in lower smoke emissions [29]. Efforts can be made to increase the calorific value of the feedstock and make it suitable for use by reducing the moisture content through drying. In addition, mixing feedstock with higher calorific valued feedstock can increase the effectiveness of solid biofuel [30], [31].

3.2. Variations in Biomass Waste Characteristics from Agriculture and Plantations

Agricultural and plantation wastes exhibit highly diverse physical, chemical, and thermal characteristics. Factors such as moisture level, ash percentage, volatile components, fixed carbon content, and calorific value significantly influence their potential to be utilized as solid fuels (such as pellets, briquettes, and charcoal briquettes). The specific characteristics of each type of waste are presented in Table 2, and visual representations of several waste types are shown in Figure 2.

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Table 2. Comparison of agricultural and plantation biomass waste properties as solid biofuel feedstock

No.	Types of biomass	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Calorific value (cal/g)	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Ref.
1	Sweet sorghum	55	3.9	-	16.3	4,299.23	-	-	-	[32]
2	Wheat straw	7.41	4.1	-	-	-	22.42	42.73	28.4	[33]
3	Jali straw	6.34	4.9	-	-	-	20.53	46.6	25.92	[33]
4	Wheat husk	7.43	3.9	-	-	-	20.54	39.22	35.23	[33]
5	Cotton stalk	8	4	74.8	13.2	3,988.73	16.5	34.2	26.7	[34]
6	Cotton bark	8	12	70	10	3,940.96	14.2	36.5	24.3	[34]
7	Oil palm stem	8.21	3.69	79.98	16.17	3,847.80	6.64	39.4	25.97	[35]
8	Oil palm frond	8.11	3.12	78.9	17.87	3,776.16	8.96	54.35	20.72	[35]
9	Oil palm kernel shell	8.92	1.35	72.58	26.14	4,471.20	38.15	37.95	11.52	[35]
10	Oil palm root	11.92	8.49	68.32	22.28	3,893.19	29.26	49	19.19	[35]
11	Oil palm decanter cake	10.38	14.79	72.13	12.75	4,060.38	20.91	21.85	13.51	[35]
12	Oil palm empty fruit bunch	8.93	5.48	79.16	15.43	4,342.22	12.16	37.82	21.85	[35]
13	Oil palm fiber	9.53	5.82	75.43	18.24	4,347	21.38	33.58	25.41	[35]
14	Corn cob	7.14	1.05	87.76	11.19	3,931.40	19.6	28.75	39.3	[36]
15	Sugarcane bagasse	5.2	4.8	86.6	13.4	3,439.38	20.3	43.4	20	[2], [37]
16	Peanut shell	5.79	4.26	84.9	13.4	4,428.20	28	48	3	[38], [39]
17	Coconut shell	5.56	1.8	70.82	21.8	4,633.61	30	65	-	[5], [40]
18	Banana skin	7.64	11.95	60.92	19.49	4,055.60	-	-	-	[3]
19	Durian skin	12.7	1.39	65.22	20.69	3,800.04	15.45	60.45	13.09	[41] – [43]
20	Coffee grounds	11.69	2.06	70.03	16.22	4,490.30	-	-	-	[44]
21	Coffee skin	8.88	0.79	75.85	14.48	3,802.43	-	-	-	[45]
22	Rice husk	-	20.26	63.52	16.22	3,783.32	19.2	34.4	29.3	[46]
23	Rice straw	-	18.67	65.47	15.86	3,604.18	20.4	44.3	35.5	[46]

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(a) (b) (c) (d) (e) (f)

Figure 2. Types of agricultural and plantation waste (a) Coconut shell [3], (b) Sugarcane bagasse [3], (c) Banana peel [3], (d) Rice husk [27], (e) Peanut shell [38], and (f) Cotton stalk [34]

Figure 2 visually shows several types of agricultural and plantation biomass wastes that are quite common and very abundant. Unfortunately, these wastes have different characteristics and have not been optimally utilized as solid biofuel feedstock. A summary of the biomass waste characteristics is provided in Table 2. Based on Table 2, agricultural and plantation waste exhibits a wide range of characteristics: moisture content ranges from 5.56–55%, ash content from 0.79–20.26%, volatile matter from 60.92–87.76%, fixed carbon from 10–26.14%, and calorific value from 3,439.38–4,633.61 cal/g. The chemical composition includes lignin, cellulose, and hemicellulose, ranging from 6.64–38.15%, 21.85–65%, and 3–39.3%, respectively. A key criterion for solid biofuel feedstock is a high calorific value. Generally, three types of biomass waste meet the best quality parameters and are highly suitable as raw materials for solid biofuel: coconut shells, coffee grounds, and oil palm kernel shells. These three types of waste all have calorific values of ≥ 4000 cal/g. These values are considered high for solid biomass, making them prime candidates for bioenergy fuel applications such as cooking, heating, and industrial use. Additionally, they have high lignin content, which enhances both calorific value and thermal stability. Lignin also acts as a natural binder, contributing to the quality of the final product and resulting in more cost-effective and economical solid fuel [28].

Konversi Energi dan Manufaktur

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Jurnal Konversi Energi dan Manufaktur
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3.2. Conversion of Agricultural and Plantation Waste Biomass into Solid Biofuels

3.2.1 Mechanical Processing

Conversion technologies are essential in shaping the potential of bioenergy generation and enhancing environmental outcomes. Higher energy conversion efficiency results in greater energy output [47]. Mechanical processing is among the most straightforward and practical techniques for transforming biomass into solid biofuel. Mechanical processing involves the use of equipment to convert biomass into a denser form. The initial preparation includes drying the biomass, grinding it into fine particles, and molding it into a specific shape. This process is a method of converting agricultural and plantation waste into solid fuel through compression and shaping without involving chemical reactions. The mechanical method is classified into two main techniques: pelletization and briquetting. A detailed explanation of each of these techniques is provided below.

3.2.2 Pelletizing and Briquetting

Pelletization is a mechanical method used to convert biomass into small, uniformly sized granules by applying high pressure combined with heat. This technique serves as an effective solution for managing waste generated from agricultural and plantation activities. The pelletization process involves several stages, including initial size reduction (pre-milling), drying, fine grinding, pellet formation, and a final cooling stage to harden the product. The main advantages of this method lie in its ease of storage and transportation due to the small and uniform shape of the pellets, as well as its minimal requirement for additional binding agents [4].

Briquetting is a mechanical technique used to shape biomass into solid briquettes of larger sizes, such as cylinders, cubes, or other forms through compaction under medium to high pressure [48]. Briquettes produced under low pressure (approximately 30–60 MPa) tend to be more fragile, whereas those formed under high pressure (150–250 MPa) are more robust and possess greater density. Applying greater pressure leads to an increase in the density of the resulting briquettes [49]. The process begins with the biomass being milled into a fine powder, after which it may be mixed with natural binding agents like starch, molasses, or resin, depending on the need. The mixture is then compacted using a briquetting machine, either a screw press or a piston press and subsequently dried to enhance its physical strength. The resulting briquettes typically have a density ranging from 0.50 to 1.3 g/cm³ and can be produced from various biomass sources, including mixtures of agricultural, plantation, and forestry waste, as well as household organic waste. As a renewable alternative energy source, briquettes are widely used at the household level and by small-scale industries, particularly in rural areas. The primary advantages of the briquetting technique lie in the diversity of feedstock. It can be utilized where the relative simplicity of the production process requires only basic equipment [1].

The briquette production process involves compressing various types of materials into a solid form under high pressure. When the raw material is wood based, the natural lignin released under pressure and acts as a binding agent between particles. During compaction, the temperature also rises sufficiently to trigger the release of adhesive substances from the raw material. One of the critical factors in this process is moisture content. The level of moisture significantly affects the success of biomass compaction. If the moisture content exceeds 20%, the biomass cannot be compacted effectively and may result in brittle briquettes. To produce high-quality briquettes, an ideal moisture content of around 15% is recommended [50].

3.2.3 Thermochemical Processing

Multiple technologies are employed to transform biomass waste into useful energy. Among them, thermochemical conversion is one of the most commonly utilized approaches for producing solid, liquid, or gaseous biofuels from biomass [51]. This method utilizes heat and chemical processes to convert organic matter into cleaner and more sustainable energy sources. The technique is considered highly promising due to its cost efficiency, rapid reaction rates, and ability to produce high-quality end products. Torrefaction, pyrolysis, gasification, and hydrothermal liquefaction are among the principal methods used in thermochemical biomass conversion [52]. Among these, pyrolysis is the most widely applied method for converting agricultural and plantation waste biomass into solid biofuel.

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In pyrolysis, the organic components of biomass experience irreversible thermochemical breakdown to generate biofuels. Pyrolysis techniques are typically divided into three categories: slow, intermediate, and fast [33]. This process thermally breaks down biomass at high temperatures—typically between 300 and 700°C—under oxygen-free conditions, generating products such as biochar, bio-oil, and non-condensable gases including H_2, CH_4, CO, and CO_2 [1].

3.3. Processing Agricultural and Plantation Waste into Energy in a Circular Economy Model

The circular economy concept embodies an economic framework that promotes sustainable development. It is designed to address the challenge of low global recycling rates, where most of the embedded energy in materials ends up in landfills. The continuous growth in waste generation per person has led to increased overall waste volumes and a greater demand for comprehensive disposal methods. As a response, waste-to-energy strategies are being more widely adopted within clean and affordable energy initiatives to support the transition toward a circular economy. This economic model promotes sustainable waste management by leveraging resources and technology to efficiently transform diverse waste materials into usable energy, thereby reducing environmental harm and generating additional energy sources [53].

Agricultural and plantation residues hold potential energy that can be utilized as feedstock for solid biofuels. Transforming this waste into pellets, briquettes, or charcoal briquettes not only helps in waste reduction but also generates new value chains within the agricultural sector. Waste that was previously burned or discarded is now processed into energy, promoting sustainability and resource efficiency [54]. Moreover, converting waste into energy generates new employment opportunities in energy production, distribution, and related sectors. This, in turn, strengthens local economies, particularly in agricultural and plantation regions. Moreover, energy derived from biomass waste can be used to fulfill the energy requirements of households and small to medium-sized enterprises (SMEs), and industries, contributing to a more decentralized and inclusive energy system.

4. Conclusion

The characteristics of various agricultural and plantation wastes indicate highly promising potential for solid biomass energy from these sources. Important indicators consist of low moisture levels, low ash content, reduced volatile matter, elevated fixed carbon, high energy value, and substantial concentrations of chemical constituents (lignin, cellulose, and hemicellulose). Those indicators are critical in determining the feasibility of agricultural and plantation residues as raw materials for solid biofuel. Among these, coconut shells, coffee grounds, and palm kernel shells exhibit particularly favorable properties that significantly influence the quality and combustion efficiency of solid biofuels. Overall, these biomass wastes not only address the challenges of renewable energy development but also serve as part of a sustainable waste management solution. They reinforce the principles of a circular economy, and contribute to the achievement of SDGs (Sustainable Development Goals), particularly Affordable and Clean Energy or SDG 7, Responsible Consumption and Production or SDG 12, and Climate Action or SDG 13.

5. Acknowledgments

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Volume 10 Number 2 – July 2025 Page 150-161
Website : http://journal.unj.ac.id/unj/index.php/jkem
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