Evaluation of Giant Miscanthus-Based Biomass Briquettes as a Sustainable Energy Source

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Abstract: This study examines the feasibility of biomass briquettes as a renewable energy source, utilizing Giant Miscanthus, sawdust, and spent coffee grounds. Recycled paper pulp serves as a binder, enhancing energy density and combustion efficiency. The briquetting process involves drying, grinding, mixing, and compressing the raw materials. Fuel characteristics were assessed through proximate and ultimate analyses, calorimetry, and thermogravimetric analysis (TG/DTA). Spent coffee grounds exhibited the highest heating value (21,370 kJ/kg), followed by sawdust (17,610 kJ/kg) and Giant Miscanthus (17,020 kJ/kg). Thermal decomposition confirmed efficient combustion, with Giant Miscanthus achieving complete combustion at 484°C and an exothermic peak at 452°C. Giant Miscanthus emerged as a promising feedstock due to its low ash content, high energy yield, and compatibility with existing infrastructure. Combining agricultural residues with non-arable crops enhances resource efficiency. This study highlights the potential of biomass briquettes to support decarbonization, energy security, and sustainable development goals by providing a viable low-carbon alternative to fossil fuels.

Keywords: binder; biomass briquettes; giant miscanthus; renewable energy; thermogravimetric analysis

INTRODUCTION

Background

The world population is expected to grow 8.2 billion by 2024, with forecasts suggesting ongoing growth, anticipated to rise to 10.3 billion by the 2080s (UN DESA, 2024). It's noteworthy that a significant portion of this population growth is concentrated in developing nations, giving rise to a myriad of challenges. Forecasts for the future indicate a swift upsurge in energy demand, coinciding with concerns pertaining to water, food, and environmental issues (Lalawmpuii & Rai, 2023). Numerous factors have been instrumental in propelling the adoption of renewable energy sources. The primary factor contributing to global warming is the attribution of carbon dioxide (CO_2) emissions to the combustion of fossil fuels (C. Chen et al., 2022). Additionally, the recent upswing in energy demand, with expectations of further expansion following economic recovery, highlights the shift toward a greater dependence on sustainable energy alternatives (IEA, 2023) .

In 2023, the global average surface temperature is roughly 1.8 °C above pre-industrial levels. This increase has instigated occurrences of heatwaves, droughts, tropical cyclones, cold snaps, and other severe weather occurrences, even as atmospheric greenhouse gases have not yet reached their maximum levels (FAO, 2023). Under the prevailing circumstances, the UN Climate Change Conference (COP21) convened in Paris, France, on 12 December 2015 to address the issue of global warming. The resulting Paris Agreement is a binding global accord endorsed by 196 Parties aimed at addressing climate change. In the Agreement, Article 2 specifies the following objectives: "limiting the global average temperature increase to well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C". Achieving this goal is acknowledged as a critical step in substantially reducing the risks and outcomes associated with global warming(Masson-Delmotte et al., 2019). Reaching the target of limiting global temperature rise to 1.5°C necessitates a reduction of around 37 gigatons (Gt) of CO_2 emissions from 2022 levels, as well as attaining net-zero emissions in energy production by 2050. An annual installation of approximately 1,000 gigawatts (GW) of renewable energy is required to remain on course for the 1.5 °C target. The imperative for substantial expansion in both the quantity and proportion of renewables such as wind, solar, and biomass is evident, a task considered both technically feasible and economically viable. In 2022, global renewable energy installed capacity reached approximately 300 GW, representing 83% of the newly installed capacity. In contrast, fossil fuel and nuclear additions together represented 17% (IRENA, 2023) .

The global power system is currently experiencing a phase of decarbonization, largely driven by the growing significance of renewable energy technologies. Notably, wind and solar energy sources are crucial in driving the expansion of power generation. Wind and solar power generation have already attained cost competitiveness compared to traditional energy generation methods. Additionally, it improves the capacity to incorporate substantial amounts of variable power sources into energy systems. The expansion of wind and solar energy demands a substantial rise in investment and the development of new capacity (bp, 2023). The COP 28 Presidency initiated the Global Renewables and Energy Efficiency Pledge, supported by 130 national governments and the European Union. This initiative aims to increase world renewable energy capacity threefold to 11,000 GW by 2030, while also doubling the annual rate of energy efficiency improvements to over 4% (UN, 2023). Global renewable energy capacity will total 7,300 GW by 2028, according to the IEA's projections based on current policies and market trends. This growth trajectory suggests that by 2030, global capacity will increase to 2.5 times its current level (IEA, 2023) . Various renewable energy sources are currently in use around the world. Biomass is a key renewable energy source, with the added benefit of being storable as a material, unlike wind and solar energy. This characteristic allows biomass to be utilized when electricity, heat, or other energy needs arise (Sanchez et al., 2022).

The global domestic biomass supplies totaled 57.5 exajoules (EJ) in 2020. The majority, accounting for 86%, was derived from solid biomass sources. Asia served as the primary contributor, representing 40% of the global supply of solid biomass. The United States of America is the leading country, supplying over 60% of the total contribution for liquid biofuels, the second-largest source. Global production statistics from 2022 indicate that solid biomass accounted for 46.4 million tons, biomass fuel amounted to 1.9 billion cubic meters, and wood charcoal production reached 54.9 million tons (WBA, 2023). The outcome yields a refined fuel that competes with the convenience and energy density of conventional fossil fuels. Briquettes are available in various sizes and configurations. Typical forms include cylindrical extrusions with diameters ranging from 25 mm to 80 mm and lengths up to 300 mm, while others are molded into rectangular parallelepiped shapes. Pellets are compacted biomass particles shaped into small cylindrical forms, typically ranging from 5 to 40 mm in length and about 7 mm in diameter, resembling the size and shape of pharmaceutical tablets. Like briquettes, pellets carry drawbacks, such as requiring protection from dust and moisture. However, they also boast significant benefits, including ease of storage, transport, combustibility, and suitability for heating equipment (IREA, 2019).

Global pellet production experienced a substantial rise between 2021 and 2022, increasing from around 44.7 million tons to approximately 46 million tons (San Miguel et al., 2022). Solid biomass fuels, including briquettes and pellets, are manufactured through the compression and shaping of biomass feedstocks such as organic waste sawdust, and forest by-products. The production of solid biomass fuel can leverage the human resources and technology available in the region where fuel is required. This is anticipated to invigorate the local economy and foster job creation (Ibitoye et al., 2023). In the manufacturing process of biomass briquettes, factors including the particle size of the biomass raw material, compression pressure, compression time, type, and quantity of binder play crucial roles. To enhance the combustion characteristics of biomass fuel, it is imperative to investigate factors such as particle size, blending ratio, compression pressure and temperature and binder (Marreiro et al., 2021). To enhance the density of biomass residue, it is essential to minimize its volume through pressure molding, thereby improving the combustion characteristics of biomass fuel. Both pressure and temperature play significant roles in this process. The correlation between pressure and temperature indicates that high pressures can be applied at low temperatures, while low pressures can suffice at high temperatures. However, temperatures exceeding 120 degrees Celsius are unsuitable for briquette formation. Parameters assessing the quality of briquettes encompass density, porosity, and durability. These parameters influence the moisture content of briquettes, impacting combustion, as well as the strength necessary for product distribution (Francik et al., 2020).

In the manufacturing of solid bio briquettes, both the technology employed, and the characteristics of biomass materials are crucial for densification and enhancing fuel quality. (Y. Chen et al., 2023). The particle size and uniformity of biomass feedstock powder are significant factors impacting the physical characteristics of briquettes. Grinding the biomass materials into finer grains enhances its density, hardness, and durability. Nevertheless, greater labor involvement in the powdering process results in higher manufacturing costs (Chaloupková et al., 2018). Biomass briquette production commonly relies on conventional densification equipment, including extrusion systems, screw presses, piston-based presses, hydraulic piston presses, and roller presses. These techniques for densification are classified into high-pressure, medium-pressure, and low-pressure compression depending on the target compaction density (Ibitoye et al., 2021). Numerous studies have investigated biomass briquetting through the application of pressure using hydraulic presses. Biomass briquettes are produced utilizing diverse resources, including palm trunks (Helwani et al., 2020), corncobs (Kpalo et al., 2020), coffee-pine wood residue (Mendoza Martinez et al., 2019), straw and banana (Duangkham & Thuadaij, 2023).

This study explores the potential of Giant Miscanthus (Miscanthus × Giganteus) as a feedstock for biomass briquette production, addressing the need for sustainable and efficient biofuel alternatives. Giant Miscanthus, a large perennial C4 plant, has gained attention for its high biomass yield and adaptability to marginal land, making its promising candidate for renewable energy applications. Despite its advantages, challenges remain in optimizing its utilization for solid biofuels, particularly in enhancing combustion efficiency and feasibility(Kowalczyk-juśko et al., 2022). While previous research has highlighted the potential of energy crops in biofuel production, studies focusing on the briquetting performance, combustion characteristics, and energy efficiency of Giant Miscanthus remain limited. This study aims to bridge this gap by evaluating its fuel properties and assessing its viability as a biomass briquette feedstock. By examining its combustion behavior, energy yield, and compatibility with existing bioenergy infrastructure, this research contributes to the development of more efficient and sustainable biomass energy solutions (Khakhula et al., 2020).

Aims

This study aims to assess the feasibility of biomass briquettes made from Giant Miscanthus, sawdust, and spent coffee grounds as a sustainable alternative energy source from the perspective of thermal analysis. A series of comprehensive analyses, including calorimetry, thermogravimetric analysis (TG/DTA), proximate analysis, and ultimate analysis, are employed to examine the fuel and combustion characteristics of each raw material. Additionally, the fuel properties of the briquettes are enhanced through the strategic blending of these individual feedstocks.

METHODS

Ultimate analysis, Proximate analysis, and Calorimetry

For the experiments conducted in this study, materials were sourced from around Ashikaga University. Sawdust was obtained from a carpentry workshop, spent coffee grounds were acquired from local convenience stores, and Giant Miscanthus, which grows in Tochigi Prefecture, was collected. Miscanthus sinensis, a hybrid of Japan's native Miscanthus species, is referred to as "Giant Miscanthus" in Europe and America, where it is commonly used as a biomass fuel source. Miscanthus is a member of the Poaceae family, this genus falls within the Panicoideae subfamily and the Andropogoneae tribe, highlighting its place in grass taxonomy. This tribe encompasses economically significant grasses such as Saccharum, Sorghum, and Zea. Notably, Miscanthus shares a close genetic relationship with Saccharum and is capable of hybridizing with it and other grass species. Miscanthus demonstrates several valuable agricultural characteristics, such as exceptional productivity, a high dry matter content, robust ratooning capacity, strong vigor, and resilience to environmental stresses. With its minimal ash production and impressive heating value, Miscanthus is an ideal candidate for use as a cellulosic feedstock in energy plants. Its versatility allows it to be employed in methanol production through gasification as well as in direct combustion to generate heat and energy (Tsuruta et al., 2017).

Before analysis, the samples were dried to eliminate extraneous moisture, ensuring uniformity in the experimental conditions. After drying, a grinding machine was used to process the samples, which were analyzed in triplicate to verify the reliability of the results. The experiment was carried out utilizing the equipment outlined in Table 1, in strict accordance with the corresponding standards.

Table 1. List of equipment and standard

Analysis Type	Equipment Used	Standard	Details
Higher Heating Value (HHV)	IKA-Calorimeter System C 5000	JIS Z7302-2	Determines the energy content of biomass resources.
Ultimate Analysis	Micro Coder JM10	JIS M8819	Analyzed carbon, hydrogen, oxygen, nitrogen, and ash.
Proximate Analysis	—	—	Aimed at understanding thermo-chemical conversion processes.
Moisture Content	EYELA Windy Oven WFO-520	JIS Z7302-3	Measures the moisture content of biomass resources.
Ash Content	YOSHIDA SEISAKUSHO CO., LTD. Coal Ash Quantitative Measurement Device (Type-1076)	JIS Z7302-4	Evaluates the ash content in biomass resources.
Volatile Matter & Fixed Carbon	YOSHIDA SEISAKUSHO CO., LTD. Volatile Content Measurement Device (Type-1070-S)	JIS M8812	Assesses the volatile matter and fixed carbon contents of biomass resources.

Thermal decomposition analysis (Simultaneous Thermogravimetry / Differential Thermal Analysis)

Thermogravimetric (TG) and differential thermal analysis (DTA) were conducted using a TG/DTA Thermogravimetric Analyzer (Seiko Instruments Inc., TG/DTA6200) under both inert and oxidizing atmospheres. A sample of approximately 8 to 10 mg was placed into a container for the measurement process. The empty container and the sample container were then placed in a simultaneous differential thermogravimetric measurement device, as illustrated in Figure 1. The specification is presented Table 2. The temperature gradually rose from 30°C to 800°C at a rate of 20°C per minute in a furnace with an airflow of 200 mL per minute. Each measurement took approximately 40 minutes.

Figure 1. TG/DTA6200

Table 2. Specification of TG/DTA6200

Manufacturer	Seiko Instruments Inc. TG/DTA6200
Specification	Temperature range: ambient temperature to 1100℃ TG: ±200mg, sensitivity 0.2μg DTA: ±1000μV, sensitivity 0.06μV Program speed: 0.01～100℃/min Maximum sample weight: 200mg Atmosphere: Air

Combustion experiments

Materials

Choosing an appropriate binder is essential for maintaining the stability and quality of biomass briquettes. Binders play an essential role in binding the biomass particles together during compression and maintaining cohesion after briquette formation. Various materials can serve as binders for biomass briquettes (Obi et al., 2022a). Starch-based binders, such as corn starch, cassava starch, or potato starch, are commonly used due to their adhesive properties and availability. When mixed with water and heated, these binders effectively hold the biomass particles together (Obi et al., 2022b). Molasses, a byproduct of sugar production, is another potential binder due to its sticky nature, which not only helps bind the particles but also imparts a slight sweetness to the briquettes (Yustanti et al., 2022). Lignin, a natural polymer found in plant cell walls, can also act as a binder when extracted from biomass sources such as wood or agricultural residues. Lignin-based binders can enhance the stability of the biomass briquettes. They are often combined with other binders to improve the calorific value of the briquettes (Wang et al., 2019). The present research examines the use of recycled paper pulp, sourced from the university's wastepaper, as the binder for producing biomass briquettes. This binder is a sustainable option that enhances the structural integrity of the briquettes after the addition of water. The selection of a binder is determined by factors including cost, availability, desired briquette properties (like strength, moisture resistance, and calorific value), and environmental considerations. Ultimate analysis and calorific value studies have been conducted for various types of waste. Recycled paper pulp has characteristics for the binder (Agrawal & Raut, 2019) and chosen to bind the briquettes, aligning with the aim of reusing wastepaper from academic institutions.

Briquette preparation

Briquetting is the method of compacting biomass materials into compact, solid briquettes that function as fuel. The objective is to enhance the energy density, transportability, and combustion performance of the biomass. A detailed breakdown of the process is provided below. The preparation of biomass feedstock involves several key steps to ensure its suitability for briquetting. First, materials are carefully selected based on their availability, energy content, and compatibility with the briquetting process. Next, the chosen biomass is dried to reduce its moisture content, which is essential for improving both combustion efficiency and briquetting performance. Ideally, the moisture content is reduced to less than 10%. Following the drying process, the biomass is ground into fine particles to achieve uniform density and enable effective compaction during briquette formation. The process of mixing biomass with binders involves two critical steps to enhance the cohesion and durability of the briquettes. First, binders such as recycled paper pulp, starch, or lignin are added, with the choice of binder depending on factors like cost, availability, and the desired properties of the final product. Next, the biomass and binder are thoroughly mixed to ensure uniform distribution and achieve optimal binding for durable and effective briquettes. The process of compression and molding involves two key steps. First, the prepared mixture is fed into a briquetting machine and compressed using a hydraulic press, as illustrated in Figure 2. Subsequently, the compacted biomass is molded into various shapes, such as cylindrical, rectangular, or customized forms, tailored to specific applications. The resulting biomass briquettes are shown in Figure 3.

Experimental setup

The experimental setup utilized a small, insulated stove specifically designed for efficient combustion of solid biomass fuels. The stove featured optimized airflow management to ensure controlled and efficient burning. Temperatures were continuously monitored using thermocouples connected to a data logger, allowing for precise data collection throughout the combustion process. The design of the stove is depicted in Figure 4.

The procedure began with the ignition of the biomass briquettes using kindling to establish a stable flame. Once the flame was steady, airflow was adjusted to achieve optimal combustion conditions. The combustion process progressed through three distinct phases: drying, devolatilization, and char oxidation. Throughout the experiment, temperature changes were meticulously recorded using a data logger, with a focus on the combustion zone and the flue gas outlet to monitor performance and efficiency.

Figure 2. Hydraulic press **Figure 3.** Biomass briquette (Left; G-M, paper, Right; G.M., Spent coffee ground, paper) **Figure 4.** Stove

RESULTS AND DISCUSSION

Proximate analysis, Ultimate analysis and Calorimetry

Proximate analysis

The proximate analysis of biomass involves assessing essential properties, including moisture, volatile substances, fixed carbon, and ash content to evaluate combustion behavior and energy potential. These factors significantly influence fuel efficiency, ignition characteristics and handling properties. High moisture content reduces calorific value, as additional energy is needed to evaporate water before combustion can occur. Lower moisture content leads to better combustion performance and higher net energy output. Volatile matter plays a crucial role in ignition and combustion speed. Biomass with a high volatile matter content ignites quickly and burns rapidly, making it suitable for efficient energy conversion. Fixed carbon represents the portion of biomass that combusts after the volatiles are released, sustaining the burn and ensuring a steady heat output. A balanced fixed carbon level contributes to both efficient ignition and prolonged burning. Ash content is a critical factor in biomass fuel quality. High ash content is undesirable as it leads to reduced energy output, increased slag formation, and higher maintenance costs for combustion systems (Racero-Galaraga et al., 2024).

Giant Miscanthus exhibits promising combustion potential, characterized by moderate moisture at 10.4 % and fixed carbon levels at 14.9%, along with relatively low ash content of 3.8%. A moderate fixed carbon level in Giant Miscanthus suggests it has a balanced combustion profile, offering both quick ignition and sustained burning. The results of the proximate analysis for Giant Miscanthus are presented in Table 3.

Table 3. Proximate analysis of Giant Miscanthus

	Giant Miscanthus
Water contents (%)	10.4
Ash (%)	3.8
Voltaic Matter (%)	70.9
Fixed Carbon (%)	14.9

Ultimate analysis

Ultimate analysis is the process of assessing the elemental composition of biomass. It specifically involves quantifying the quantifying the quantities of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O). These elements are essential for assessing the fuel's energy content, combustion characteristics, and environmental effects.

In this study, ultimate analysis was performed on Giant Miscanthus, spent coffee grounds, sawdust, straw, rice husk, and wastepaper, as presented in Table 4.

Carbon is the primary element accountable for heat generation during combustion. Higher carbon content generally means higher energy potential. In the study, spent coffee grounds had the highest carbon content (49.65%), followed by sawdust and Giant Miscanthus. Hydrogen is another important element for energy generation, as it burns to produce water vapor and contributes to heat release. Spent coffee grounds had the highest hydrogen content (7.08%), suggesting it would contribute significantly to the calorific value. Nitrogen is not a fuel component but affects combustion and emissions. It can form nitrogen oxides (NOx), pollutants harmful to the environment. The nitrogen content was relatively low across all feedstocks, with Giant Miscanthus having 0.42% and sawdust at 0.40%. Oxygen is a product of biomass's organic compounds, but it also reduces the calorific value, as it is part of the combustion process. Giant Miscanthus had a higher oxygen content (44.28%), which can lower its overall energy output.

Giant Miscanthus possesses moderate carbon content, enhancing its energy potential. Its relatively low nitrogen content (0.42%) indicates minimal NOx (nitrogen oxide) emissions during combustion, contributing to its environmental benefits. Although the high oxygen content (44.28%) slightly diminishes its calorific value, it remains a viable biofuel due to its favorable combustion characteristics.

Spent coffee grounds exhibit the highest carbon (49.65%) and hydrogen (7.08%) content among the materials analyzed, making it the most energy-dense fuel in the study. However, its nitrogen level (2.47%) exceeds that of the other feedstocks, which could lead to elevated NOx emissions during combustion.

Sawdust has a well-balanced elemental composition, featuring moderate carbon and hydrogen content, making it a suitable source of energy for biomass fuel. Its relatively low nitrogen content (0.40%) suggests that it is unlikely to generate significant NOx emissions during combustion, which helps in reducing air pollution. However, the high oxygen content (44.89%) reduces the overall calorific value of sawdust when compared to materials with lower oxygen content.

Calorimetry

Calorimetry is the process of quantifying a fuel's calorific value, providing key data to evaluate its viability and efficiency as an energy source. The calorific value represents the energy released for each unit of weight during combustion. Biomass fuels with higher calorific values are considered more efficient, as they generate greater energy output. HHV, a crucial metric in calorimetry, represents the total energy released during the full combustion of biomass, including the energy required to vaporize the moisture produced in the process. This comprehensive measure captures the maximum energy potential of the fuel, making it critical for evaluating its suitability for bioenergy applications (Alruqi et al., 2024). The calorimetry analysis results presented in Table 3 highlight the energy content of various biomass samples.

Spent Coffee Grounds had the highest calorific value at 21,370 kJ/kg (5,100 kcal/kg), making it the most energy-dense fuel in the study. Sawdust exhibited a calorific value of 17,610 kJ/kg (4,200 kcal/kg), slightly higher than Giant Miscanthus but still lower than spent coffee grounds. Giant Miscanthus had an HHV of 17,020 kJ/kg (4,070 kcal/kg), indicating a moderate energy output compared to other materials. Straw showed a calorific value of 15,270 kJ/kg (3,650 kcal/kg), which is lower than sawdust and Giant Miscanthus but still viable for biomass fuel. Rice Husk and Wastepaper had the lowest calorific values, 13,940 kJ/kg (3,330 kcal/kg) and 13,040 kJ/kg (3,110 kcal/kg), respectively, indicating lower energy output.
In summary, spent coffee grounds offer the highest energy potential, while rice husk and wastepaper have the lowest, with sawdust and Giant Miscanthus providing moderate calorific values suitable for biomass applications.

Table 4. Ultimate analysis and Calorimetry of Giant Miscanthus

	C (%)	H (%)	N (%)	O (%)	HHV (kJ/kg)	HHV (kcal/kg)
Giant Miscanthus	44.69	5.90	0.42	44.28	17,020	4,070
Spent coffee ground	49.65	7.08	2.47	35.94	21,370	5,100
Sawdust	45.36	5.93	0.40	44.89	17,610	4,200
Straw	38.66	5.51	0.85	45.32	15,270	3,650
Rice Husk	33.40	4.70	0.59	37.03	13,940	3,330
Waste Paper	37.9	5.77	0.00	45.93	13,040	3,110

Thermal decomposition analysis (Simultaneous Thermogravimetry / Differential Thermal Analysis)

The TG analysis demonstrated a continuous and progressive weight reduction, as evidenced by the downward trends of the curves observed at different heating rates. This trend clearly demonstrates that, with increasing temperature, the samples undergo a stepwise thermal degradation process, primarily affecting the lignocellulosic components, which include hemicellulose, cellulose, and lignin. The TG curve provides a detailed depiction of changes in the sample's weight relative to ambient temperature, capturing these variations over time or as a function of temperature increments. Similarly, the DTA curve acts as a complementary tool, providing insights into the magnitude and nature of thermal events. These reactions include processes that absorb heat and those that release heat during the combustion or decomposition of biomass (El-Sayed, 2019). Furthermore, by calculating the area under the DTA peaks, it becomes possible to quantitatively estimate the heat content of the material, providing crucial data for evaluating its energy potential and thermal behavior under different conditions.

Giant Miscanthus

Figure 4 displays the thermal decomposition analysis of Giant Miscanthus, highlighting its behavior under increasing temperature. The TG curve displays a 9.1% weight loss at approximately 260°C, mainly attributed to moisture evaporation, signifying the initial drying phase. As the temperature rises, the sample undergoes further decomposition, with complete combustion occurring at 484°C, where no additional weight loss is observed, stabilizing at 96.3%. The DTA curve indicates a significant exothermic peak at 452°C, reaching 15.6 µV. This peak reflects the release of significant heat during the breakdown of lignocellulosic components, such as hemicellulose and cellulose. The results suggest that Giant Miscanthus exhibits favorable thermal stability and efficient combustion, making it a promising candidate for bioenergy applications.

The TGA curve undergoes three phases of decomposition pre-heating phase (moisture evaporation), volatile devolatilization, and carbonization (Onokwai et al., 2022). The thermal decomposition analysis confirms that Giant Miscanthus possesses high volatile matter for easy ignition, moderate fixed carbon for sustained combustion making it an efficient biofuel. With a high HHV of 17,020 kJ/kg and low ash content, it delivers strong energy output and cleaner combustion, reducing operational and maintenance challenges in biomass energy systems.

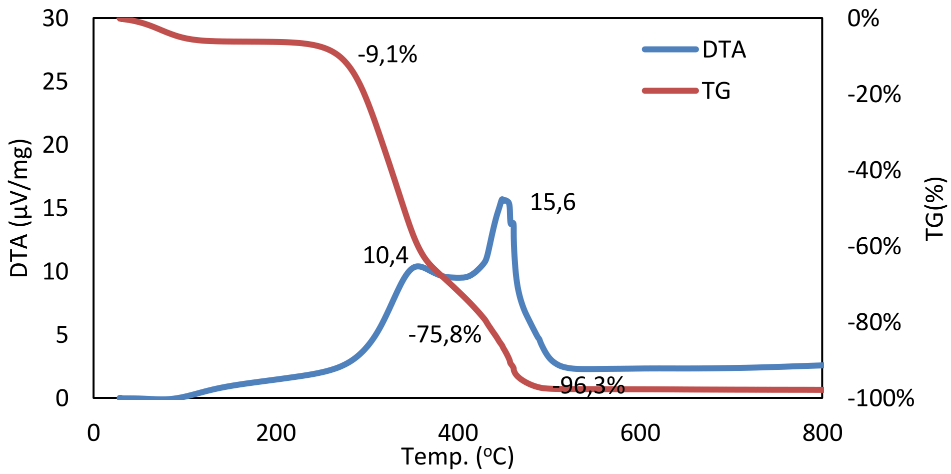

Figure 5. Thermal decomposition of Giant-Miscanthus

Spent coffee grounds

Figure 5 presents the thermal decomposition analysis of spent coffee grounds, illustrating their behavior under thermal stress. The ultimate analysis of coffee husk and coffee wood confirms their suitability as potential feedstocks for biomass briquette production (Sukarta et al., 2023). The TG curve shows an initial mass reduction of 14.4% at approximately 240°C, mainly attributed to the evaporation of moisture. As the temperature increases, further decomposition occurs, culminating in complete combustion at 592°C, with a final weight stabilization at 97.9%. The DTA curve displays a significant exothermic peak at 585°C, reaching 11.9 µV, indicating substantial heat release during the burning of volatile compounds and fixed carbon. The high combustion temperature and substantial energy release suggest that spent coffee grounds possess excellent thermal properties, making them a highly energy-dense and efficient biomass fuel.

Spent coffee grounds peak at 585°C (11.9 µV), ensuring sustained heat release, while Giant Miscanthus peaks earlier at 452°C (15.6 µV), enabling rapid combustion for quick heat applications. Spent coffee grounds deliver higher energy output than Giant Miscanthus, but Giant Miscanthus burns cleaner with lower ash content, minimizing maintenance in biomass systems.

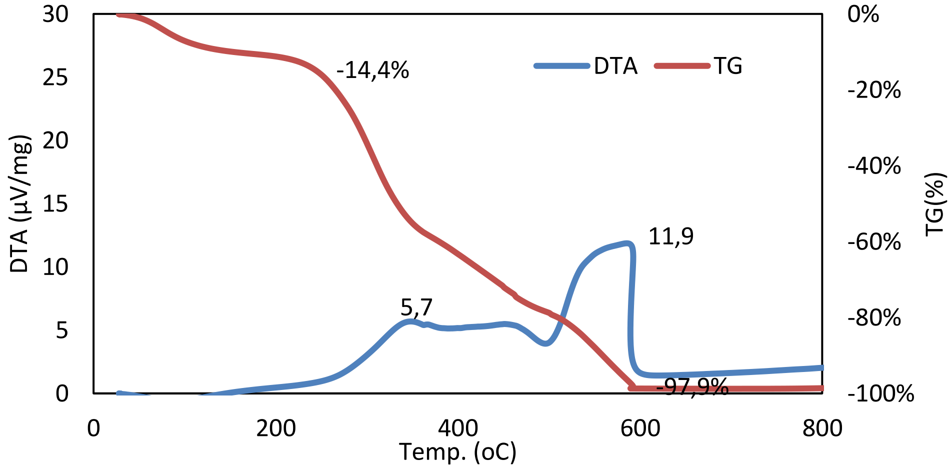

Figure 6. Thermal decomposition of spent coffee grounds

Sawdust

Figure 6 presents the thermal decomposition analysis of sawdust, highlighting its behavior under heat exposure. The similar experiment was conducted by using TG and TGA analysis (Guida et al., 2019). The TG curve indicates an initial mass reduction of 8.8% at approximately 270°C, attributed to moisture evaporation. As the temperature rises, sawdust undergoes further decomposition, with complete combustion occurring at 500°C, where no additional weight loss is observed. The DTA curve reveals two significant exothermic peaks. The first and most prominent peak appears at 360°C, reaching 37.3 µV, indicating the combustion of volatile compounds and the breakdown of cellulose. The second peak at 483°C, with a value of 21.2 µV, reflects the combustion of lignin and residual carbon. These results demonstrate that sawdust combusts efficiently, with multiple stages of heat release, making it a suitable biomass fuel with moderate energy potential.

Sawdust peaks at 360°C (37.3 µV) with higher intensity, enabling strong initial energy release, while Giant Miscanthus peaks at 452°C (15.6 µV) for uniform combustion. Sawdust's HHV slightly exceeds Giant Miscanthus, but Giant Miscanthus burns cleaner with lower ash content reducing maintenance needs.

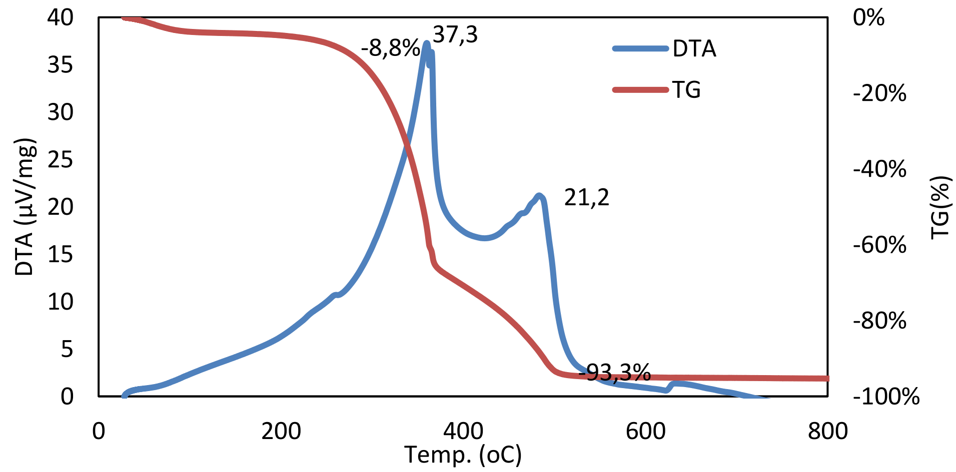

Figure 7. Thermal decomposition of sawdust

Rice straw

Figure 7 illustrates the thermal decomposition analysis of rice straw, showing its behavior under increasing temperatures. The TG curve shows an initial mass reduction of 13.4% at approximately 200°C, primarily due to moisture evaporation. Complete combustion occurs at 528°C, with a total weight reduction of 83.8%, signifying the full decomposition of the sample. The DTA curve reveals two notable exothermic peaks. The primary peak at 493°C, reaching 11.0 µV, corresponds to the combustion of fixed carbon and lignin. A secondary peak at 331°C, with a value of 7.0 µV, indicates the breakdown of hemicellulose and other volatile compounds. These findings suggest that rice straw exhibits a two-stage combustion process, with moderate energy release, making it a viable but less energy-dense biomass fuel compared to other feedstocks.

TG-DTA analysis for the rice straw was conducted by Indian institution. In the results, there is a single peak, and the peak temperature is 312°C at the heating rate of 15 °C/min (Sakhiya et al., 2021). In this experiment, rice straw undergoes two-stage combustion 493°C (11.0 µV) and 331°C (7.0 µV) with gradual energy release, while Giant Miscanthus peaks at 452°C (15.6 µV) for stronger, uniform combustion. Giant Miscanthus offers higher HHV and lower ash content, ensuring cleaner burning and reduced maintenance compared to rice straw's higher residue accumulation.

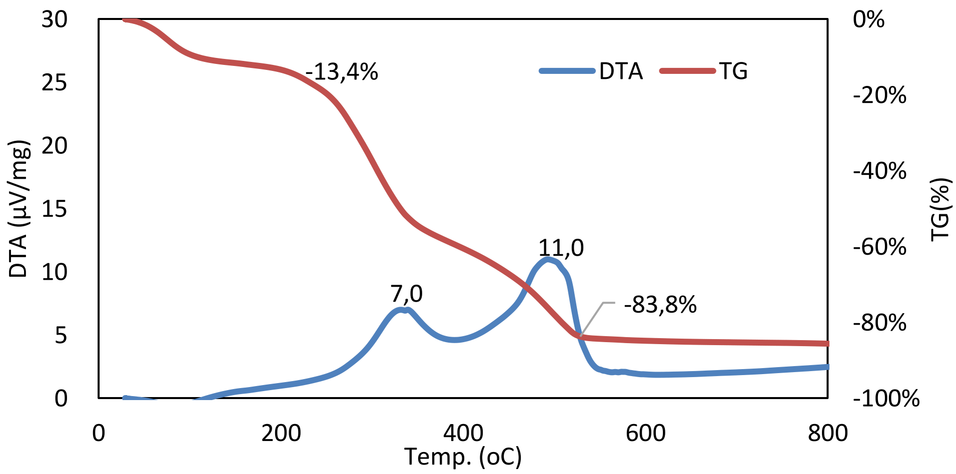

Figure 8. Thermal decomposition of rice straw

Rice husk

Figure 8 depicts the thermal decomposition analysis of rice husk, highlighting its response to elevated temperatures. The TG curve shows an initial mass reduction of 11.7% at approximately 258°C, attributed to moisture evaporation. Complete combustion is achieved at 502°C, with a total weight reduction of 77.2%, indicating full decomposition of the sample. The DTA curve features two significant exothermic peaks. The main peak at 463°C, reaching 10.6 µV, is linked to the combustion of fixed carbon and lignin. The secondary peak at 362°C, with a value of 7.9 µV, reflects the breakdown of volatile compounds, including hemicellulose. These results indicate that rice husk undergoes a multi-stage combustion process, releasing moderate amounts of energy, making it a potential but less energy-dense biomass fuel compared to others like spent coffee grounds.

TG-DTA analysis for the rice straw was conducted by Malaysian institution. In the results, there are two peaks, and the peak temperature is 376°C and the second peak is 320°C at the heating rate of 80 °C/min and nitrogen atmosphere (Balasundram et al., 2018). In this experiment, Rice husk undergoes multi-stage combustion, 463°C (10.6 µV) and 362°C (7.9 µV) with moderate energy output, while Giant Miscanthus peaks at 452°C (15.6 µV) for stronger and uniform combustion. Giant Miscanthus offers higher HHV and lower ash content, ensuring cleaner burning and reduced maintenance compared to rice husk's higher residue accumulation.

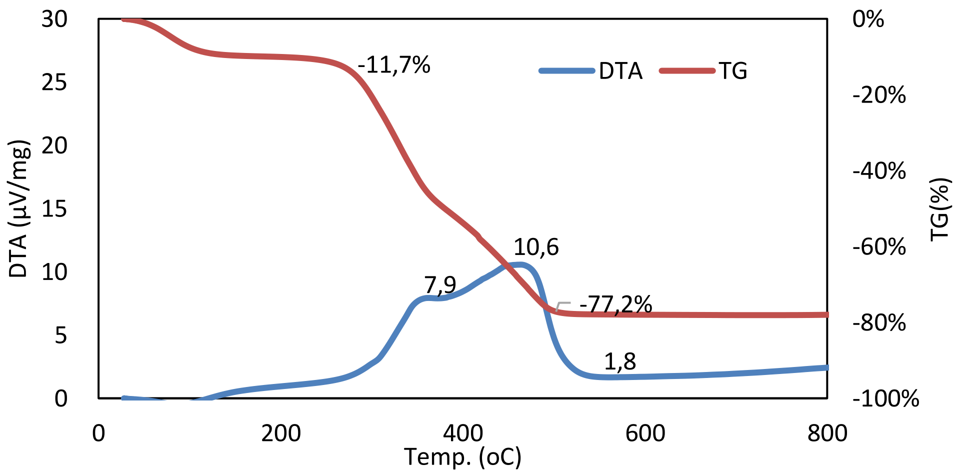

Figure 9. Thermal decomposition of rice husk

Wastepaper

Figure 9 presents the thermal decomposition analysis of wastepaper, demonstrating its thermal behaviour as the temperature increases. The TG curve shows an initial mass reduction of 7.9% at approximately 290°C, mainly attributed to the evaporation of moisture. As the temperature rises, the rate of weight loss diminishes, with a significant reduction of 84.7% at 444°C. Complete combustion is achieved at 724°C, with a total weight loss of 91.5%, signifying that the sample is fully decomposed by this point. The DTA curve reveals two notable exothermic peaks. The first peak occurs at 383°C, reaching 14.9 µV, indicating the combustion of volatile components. The second peak at 445°C, with a value of 13.8 µV, corresponds to the oxidation of remaining carbon and lignin. These findings suggest that wastepaper undergoes a two-stage combustion process, with moderate heat release, making it a viable, albeit less energy-dense, biomass fuel compared to other feedstocks.

Wastepaper undergoes two-stage combustion, 383°C (14.9 µV) and 445°C (13.8 µV) with moderate energy output, while Giant Miscanthus peaks at 452°C (15.6 µV) for stronger, uniform combustion. Giant Miscanthus has a higher HHV (17,020 kJ/kg) and lower ash content ensuring cleaner burning and reduced maintenance compared to wastepaper's higher residue accumulation.

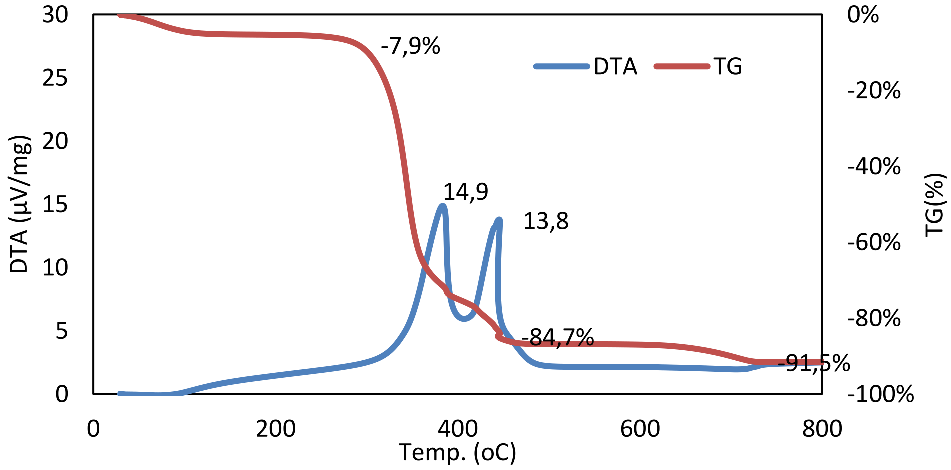

Figure 10. Thermal decomposition analysis of wastepaper

Combustion experiments

Figure 10 illustrates the estimated DTA values for a briquette mixture comprising 50% Giant Miscanthus, 30% coffee grounds, and 20% binder, based on thermal analysis. Figure 11 shows the estimated DTA values for a composition containing 80% Giant Miscanthus and 20% binder. The HHV for the first briquette composition is estimated at 17,529 kJ/kg, while the second composition, consisting of Giant Miscanthus and wastepaper, is estimated at 16,224 kJ/kg. Figure 12 illustrates the combustion performance of the two briquette mixtures. The GM80%, Paper 20% briquette reached a maximum temperature of 613.6°C, reflecting steady and controlled combustion. In contrast, the GM50%, Coffee 30%, Paper 20% briquette achieved a higher peak temperature of 677.1°C, indicating superior combustion efficiency, attributed to the higher energy content of spent coffee grounds. The rapid temperature rise and sustained high-temperature combustion observed in the GM50/ Coffee30/ Paper20 briquette highlight its enhanced performance. The addition of coffee grounds not only increases the energy output but also extends the temperature range, creating more frequent high-temperature zones. This result aligns with the findings from the thermal analysis, confirming that spent coffee grounds significantly improve combustion efficiency and prolong the burning duration of the briquette.

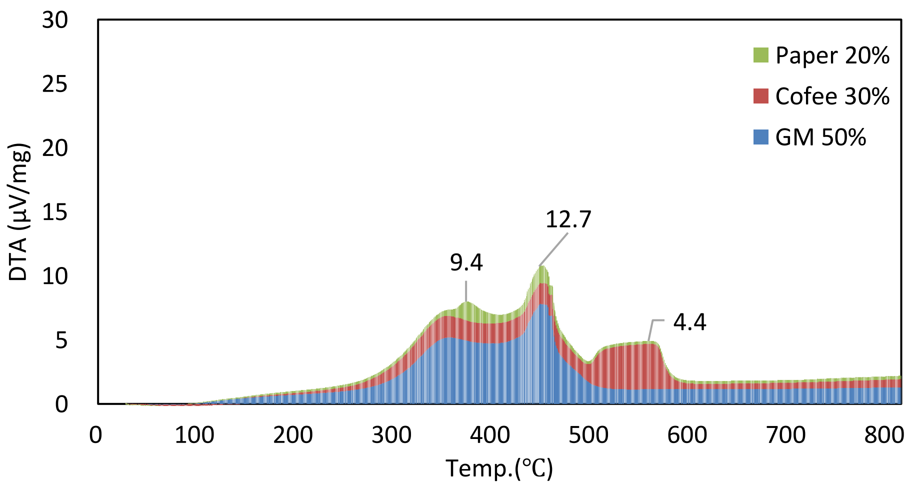

Figure 11. Estimated DTA (GM50%, Coffee 30%, Paper 20%)

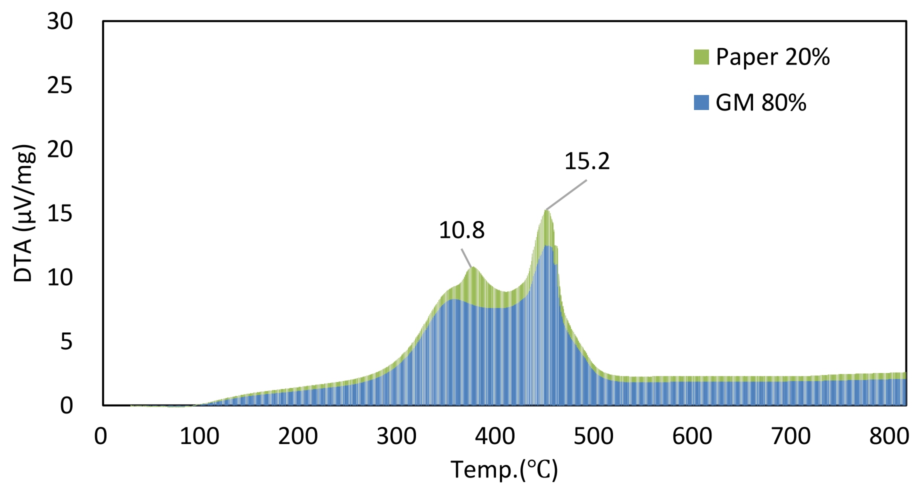

Figure 12. Estimated DTA (GM80%, Paper 20%)

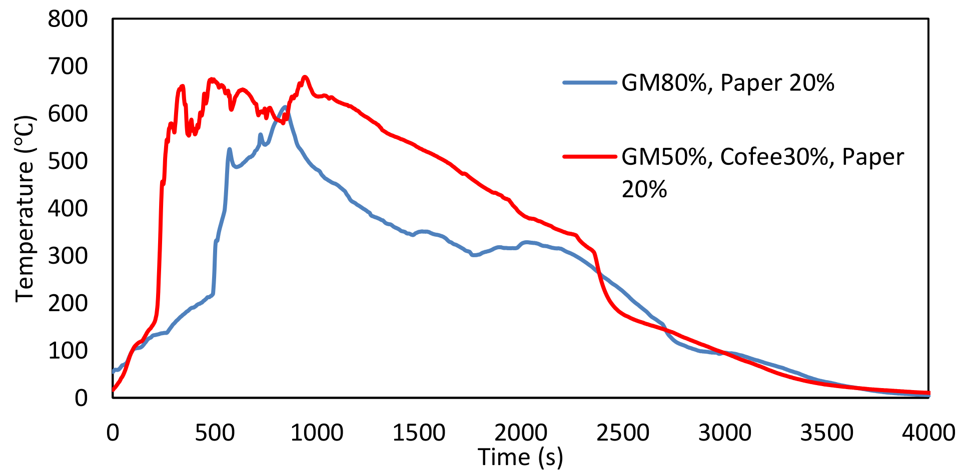

Figure 13. Combustion of Briquettes

Environmental considerations were fundamental to this study to ensure the sustainability and ecological viability of biomass fuels. Biomass serves as a renewable energy source that aids in climate change mitigation through its carbon-neutral cycle, where the CO_2 emitted during combustion is reabsorbed during plant growth. The study assessed ash content, nitrogen levels, and emission profiles to minimize the environmental impact of biomass use, with a focus on reducing air pollution, soil contamination, and waste production. Utilizing agricultural by-products, such as sawdust and spent coffee grounds, along with non-arable crops like Giant Miscanthus, fosters resource efficiency and eliminates competition with food production. These methods are consistent with the principles of a closed-loop economy, converting waste into vital energy resources. Furthermore, the research supports global climate and energy initiatives, including the Paris Agreement, by advocating for biomass as a sustainable and eco-friendly alternative to fossil fuels. By addressing local environmental challenges, such as air quality and waste management, while also supporting global decarbonization objectives, the research highlights the dual benefits of environmental conservation and renewable energy advancement.

The low nitrogen content in Giant Miscanthus (0.42%) and sawdust (0.40%) suggests minimal NOx (nitrogen oxide) emissions during combustion, contributing to better air quality. Spent coffee grounds, despite high energy density, contained 2.47% nitrogen, which could lead to increased NOx emissions, requiring mitigation measures during combustion.

These biomass materials, particularly Giant Miscanthus, are both a sustainable and carbon-neutral resource. The CO_2 released during combustion is absorbed by plants during their growth, leading to a net decrease in greenhouse gas emissions when compared to fossil fuels. Utilizing agricultural residues (e.g., sawdust, coffee grounds) and dedicated energy crops (Giant Miscanthus) prevent waste accumulation and mitigates environmental pollution. Giant Miscanthus grows on marginal lands unsuitable for food crops, minimizing competition with food production and preserving biodiversity in fertile areas.

The thermal decomposition properties of these biomass materials demonstrate their suitability for sustainable energy production. Giant Miscanthus stands out as a highly promising feedstock due to its efficient combustion, low ash content, and minimal NOx emissions. Additionally, its ability to thrive on underutilized lands offers a sustainable substitute for traditional fossil fuels. With proper optimization and emissions control, these biomass fuels can significantly contribute to global decarbonization efforts.

CONCLUSION

The study investigates the feasibility of producing biomass briquettes using Giant Miscanthus (Miscanthus × giganteus), sawdust, and spent coffee grounds as primary feedstocks, with recycled paper pulp as a binder. The briquetting process involved drying, grinding, mixing the biomass with the binder, and compressing the mixture into solid briquettes. The fuel properties of the briquettes were evaluated through proximate and ultimate analyses, calorimetry, and thermogravimetric analysis (TG/DTA). Spent coffee grounds exhibited the highest heating value (21,370 kJ/kg), followed by sawdust (17,610 kJ/kg) and Giant Miscanthus (17,020 kJ/kg). Thermal decomposition analysis revealed efficient combustion properties, with Giant Miscanthus achieving complete combustion at 484°C and exhibiting an exothermic peak at 452°C, indicating favorable thermal stability.

Combustion experiments demonstrated that briquettes containing higher proportions of spent coffee grounds achieved faster ignition, higher peak temperatures, and prolonged combustion, emphasizing their efficiency as a renewable energy product. The environmental analysis highlighted the low ash content and minimal nitrogen oxide emissions of Giant Miscanthus, which, combined with its ability to grow on marginal lands, underscores its potential as a sustainable biomass feedstock.

The findings confirm that biomass briquettes are a viable renewable energy source. They support global decarbonization efforts and provide sustainable heating and power, particularly for off-grid applications. In Japanese winters, biomass briquettes offer a stable and cost-effective alternative to fossil fuels for greenhouse heating. This ensures optimal growing conditions while reducing energy costs. Utilizing agricultural residues enhances waste valorization and minimizes environmental impact. It also aligns with circular economic principles, promoting resource-efficient energy solutions.

Future work will focus on optimizing the briquetting process, including refining compression parameters, exploring alternative binders, and integrating advanced thermal conversion technologies to enhance energy output and combustion efficiency. Expanding the geographic scope of biomass resource assessment and conducting life-cycle analyses will further validate the environmental and economic benefits of biomass briquettes.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest with any party.

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