



REVIEW ARTICLE

**A REVIEW ON PRODUCTION AND PERFORMANCE EVALUATION OF
BRIQUETTES FROM RICE HUSK, SAWDUST, AND BLACK-CURRENT LEAVES
FOR SUSTAINABLE ENERGY PRODUCTION**

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ABSTRACT

The global search for sustainable and decentralized energy solutions has resulted in increased interest in biomass briquetting technologies. This study presents a review of briquettes produced from rice husk, sawdust, and black-currant leaves, focusing on physicochemical properties, combustion performance, thermogravimetric behaviour, and techno-economic feasibility. The review was conducted using Scopus and Google Scholar databases for studies published between 2020 and 2025. An initial pool of 213 articles was screened using defined inclusion criteria, resulting in 46 relevant studies for detailed analysis. The results indicate that sawdust exhibits superior fuel properties with calorific values of 16–19 MJ/kg and low ash content (0.5–3%), leading to higher thermal efficiency (30–35%), while rice husk shows high ash content (15–25%) due to silica, which limits combustion efficiency. Black-currant leaves demonstrate high volatile matter (62–68%), enhancing ignition but requiring binder support due to low lignin content. Thermogravimetric analysis reveals three-stage degradation behaviour with activation energies ranging from 160–250 kJ/mol. Composite briquettes improve combustion stability by balancing ignition and durability characteristics. Techno-economic analysis shows production costs of 30–55 USD/tonne with potential profit margins of 40–50% under favourable conditions. Despite increasing research on biomass briquetting, studies are largely concentrated on conventional feedstocks such as rice husk and sawdust, while leaf biomass like black-currant leaves remains insufficiently characterized, particularly in terms of densification and combustion behaviour. In addition, most studies assess physicochemical, combustion, or thermogravimetric properties in isolation, with limited integration into a unified framework linked to real stove performance.

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1.0 Introduction

Global energy demand continues to increase while many developing countries remain heavily dependent on traditional biomass fuels such as firewood and charcoal. This dependence contributes to deforestation, environmental degradation, and indoor air pollution (Kpalo et al., 2022; Yunusa et al., 2024). Biomass briquetting has emerged as a promising strategy for converting agricultural and forestry residues into densified solid fuels with improved energy density and combustion efficiency.

Densification technologies such as briquetting and pelletization compress low-density biomass materials into compact fuel forms, improving handling, transportation, and storage characteristics (Tumuluru et al., 2020; Kaliyan and Morey, 2020). These technologies also facilitate the integration of agricultural residues into modern renewable energy systems (Bhattacharya et al., 2021; Mukherjee and Halder, 2021). Among the most widely range of biomass residues available globally, rice husk and sawdust have received considerable

attention because of their abundance and favourable lignocellulosic composition (Saeed *et al.*, 2021; Kpalo *et al.*, 2022). However, research is increasingly exploring alternative biomass feedstocks, including horticultural residues and leaf biomass, to enhance resource utilization and diversify biomass energy systems.

The scale of the global energy access challenge provides critical context for understanding the urgency of biomass briquetting research. According to the International Energy Agency, approximately 770 million people worldwide still lack access to electricity, and over 2.6 billion people rely on solid biomass fuels for cooking and heating (IEA, 2023). In sub-Saharan Africa and South Asia, where energy poverty is most acute, the proportion of households dependent on firewood, agricultural residues, and charcoal often exceeds 70% of the rural population (Kpalo *et al.*, 2022). The combustion of these traditional fuels in open fires and inefficient cookstoves generates high levels of carbon monoxide, fine particulate matter (PM_{2.5}), and polycyclic aromatic hydrocarbons, which are directly linked to over 3.2 million premature deaths annually from household air pollution (WHO, 2022). Beyond health impacts, the unsustainable harvesting of woody biomass for fuel drives deforestation at rates of approximately 10 million hectares per year globally, exacerbating carbon emissions and biodiversity loss (FAO, 2022). This converging health, environmental, and energy security challenges underscore the need for improved solid fuel alternatives that can be produced and distributed at the community level.

Biomass briquetting addresses these challenges by transforming low-density, dispersed agricultural and forestry residues into uniform, high-density solid fuel blocks that can be efficiently handled, stored, transported, and combusted. Unlike raw biomass, densified briquettes exhibit volumetric energy densities typically two to five times greater than loose feedstock, making them suitable for use in improved cookstoves, institutional stoves, and small-scale industrial boilers (Tumuluru *et al.*, 2020; Mohammadi *et al.*, 2021). The densification process also reduces moisture content, inhibits microbial degradation during storage, and produces a more standardized fuel product that is amenable to quality certification and commercial distribution (Oberberger and Thek, 2020). Furthermore, by valorizing agricultural residues that would otherwise be open-burned or left to decompose in fields, briquetting reduces greenhouse gas emissions and provides an additional revenue stream for smallholder farmers and agro-processing enterprises (Mukherjee and Halder, 2021). These combined benefits have attracted increasing interest from governments, development organizations, and private sector actors in biomass-rich developing economies, particularly across West Africa, East Africa, and South and Southeast Asia (Mukherjee and Halder, 2021).

Rice husk is one of the most abundant cereal processing by-products worldwide, with global production estimated at approximately 120–140 million tonnes per year, of which Nigeria alone generates over 1.8 million tonnes annually (Saeed *et al.*, 2021; Yunusa *et al.*, 2024). Despite its high silica content, which limits its calorific value and increases ash residue, rice husk possesses sufficient energy density to serve as a viable briquette feedstock when blended with higher-energy components (Yunusa *et al.*, 2024). Sawdust is produced in wood processing mills and furniture manufacturing enterprises. It is widely available and inexpensive. It has good combustion properties. This is because it contains a high amount of lignin (Akowuah *et al.*, 2020). Lignin acts as a natural binder during densification. It also improves the mechanical durability of the finished briquettes. (Nworie *et al.*, 2024; Akowuah *et al.*, 2020). The abundance of both materials in close proximity to agricultural and forestry processing centres in many developing countries makes them logistically attractive feedstocks for decentralized briquette production enterprises.

The incorporation of leaf biomass into briquette formulations represents a more recent and less thoroughly explored frontier in densified fuel research. Leaf biomass, including species-specific horticultural residues such as black-currant (*Ribes nigrum*) leaves, are generated in large quantities by fruit-growing industries, urban landscaping activities, and agro-forestry systems. These materials are predominantly discarded as low-value waste, yet their relatively high volatile matter content confers potential advantages for composite briquette formulations by improving ignition characteristics and reducing light-off times compared to more recalcitrant feedstocks (Suryajaya, 2025; Titi *et al.*, 2022). Black-currant cultivation is economically significant in parts of Northern Europe, Central Asia, and temperate regions of Africa, where leaf litter from pruning and harvesting operations constitutes a substantial seasonal biomass stream. The phytochemical and structural properties of black-currant leaves, including their cellulose, hemicellulose, and lignin fractions, have been preliminarily characterized (Suryajaya, 2025), but their thermal degradation behaviour, combustion kinetics, and performance as a briquette component have received very limited systematic attention in the peer-reviewed literature.

A critical consideration in briquette production is the multi-dimensional nature of fuel quality assessment. Unlike conventional fossil fuels, the performance of biomass briquettes is sensitive to a complex interplay of feedstock composition, pre-treatment methods, binder type, compaction pressure, and moisture content at the point of densification (Mani *et al.*, 2020; Kaur and Singh, 2023). Proximate and ultimate analysis parameters including volatile matter, fixed carbon, ash content, moisture content, and elemental composition, are used to evaluate the theoretical combustion potential of a briquette. For example, a higher volatile matter content enhances ignition and flame stability, while fixed carbon contributes to sustained combustion. In contrast, high ash content reduces combustion efficiency, and moisture content lowers the effective heating value Shen *et al.*, 2020). Thermogravimetric analysis (TGA), on the other hand, provides detailed kinetic information on the thermal decomposition behaviour of the fuel. The TGA curve (mass loss versus temperature) and its derivative (DTG curve) show distinct stages of drying, devolatilization, and char combustion, thereby revealing the reactivity and stability of the briquette under controlled heating conditions (Liu *et al.*, 2021). Practical combustion testing in representative stove systems then translates these material properties into real-world performance metrics such as thermal efficiency, burning rate, specific fuel consumption, and emission factors. The integration of all three analytical layers physicochemical characterization, TGA kinetics, and combustion testing within a unified framework is essential for developing briquettes that are not only theoretically optimal but practically deployable across household and institutional energy applications.

The techno-economic dimension of briquette production is equally important in determining whether laboratory-scale insights can be translated into viable community-level enterprises. Small and medium-scale briquette production systems must demonstrate acceptable returns on investment within the economic realities of low-income rural communities, where access to capital, technical expertise, and organized supply chains may be limited (Tripathi *et al.*, 2020; Kpalo *et al.*, 2022). The selection of locally available feedstocks, appropriate briquetting technologies (manual, hydraulic, or screw-press), and suitable binder materials therefore involves trade-offs that extend beyond pure engineering performance to encompass economic sustainability, environmental impact, and social acceptability. A review that synthesizes findings across all of these dimensions is therefore valuable not only for advancing scientific understanding but also for informing practical policy and investment decisions in the biomass energy sector.

Despite the growing body of literature on biomass briquetting, to the best of our knowledge, no previous review has specifically examined the combined use of rice husk, sawdust, and black-currant leaf biomass as a composite feedstock system, nor has prior work comprehensively integrated the combustion kinetics, TGA behaviour, and techno-economic assessment of this particular feedstock combination within a single analytical framework. The novelty of the present review therefore lies in its focus on this specific three-component feedstock system, its inclusion of an emerging horticultural residue (black-currant leaves) alongside conventionally studied materials, and its effort to bridge the gap between material science characterization and real-world energy and livelihood applications.

This review therefore aims to: (i) synthesize current literature on the physicochemical and combustion properties of briquettes derived from rice husk, sawdust, and black-currant leaf biomass; (ii) examine thermogravimetric degradation behaviour and kinetic parameters relevant to these feedstocks; (iii) evaluate the techno-economic feasibility of decentralized briquette production; and (iv) identify critical gaps that warrant further experimental and field-based investigation.

2. Method

This review was conducted through a search of peer-reviewed literature published between 2020 and 2025 following the steps highlighted in Figure 1. Electronic databases including Scopus and Google Scholar were searched using combinations of keywords such as “biomass briquettes,” “rice husk briquettes,” “sawdust densification,” “leaf biomass fuel,” “black-currant biomass,” “thermogravimetric analysis biomass,” and “techno-economic briquette production.” The search was restricted to English-language publications and excluded conference abstracts without full-text availability.

An initial search returned over 213 articles, of which 46 studies were selected for detailed review based on their relevance to the three primary feedstocks (rice husk, sawdust, and black-currant leaf biomass), their coverage of physicochemical characterization, combustion performance, thermogravimetric analysis, or techno-economic assessment, and their methodological quality. Studies were excluded if they did not report original experimental data or did not relate to solid fuel densification. The selected literature was then

synthesized thematically across six analytical domains: feedstock characteristics, combustion performance, TGA and kinetics, carbonization and pre-treatment, techno-economic feasibility, and research gaps.

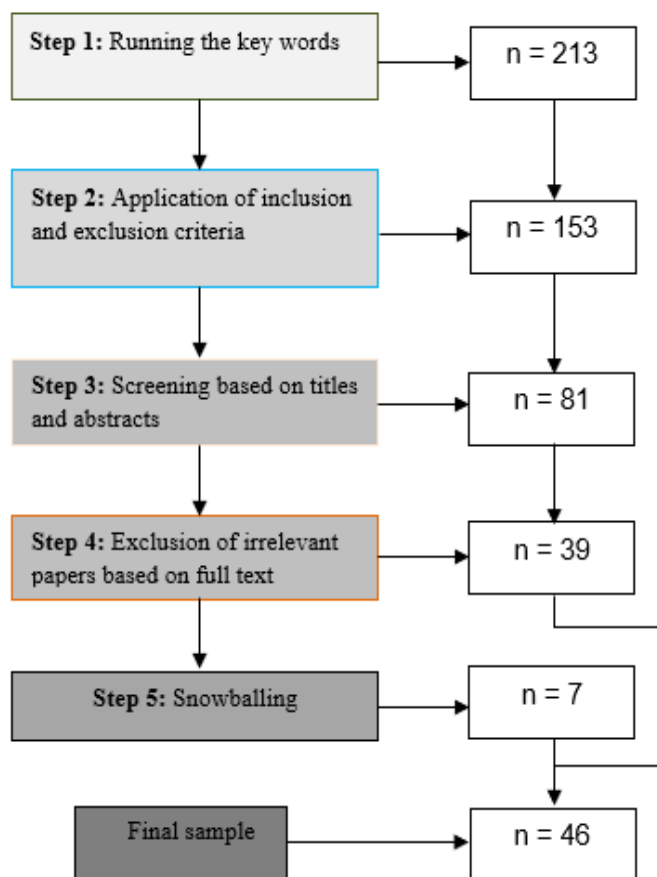


Figure 1: Flowchart of the data collection

Data extraction focused on proximate and ultimate analysis values, calorific values, activation energies, thermal efficiency measurements, and reported production costs. Where multiple studies reported data on the same feedstock, values were compared and ranges reported to reflect variability across different production contexts.

3. Findings of the Review

3.1 Overview of Biomass Briquetting Research

Biomass briquetting research has expanded significantly during the past decade (Mani *et al.*, 2020; Obernberger and Thek, 2020 etc.) explored sustainable approaches for converting agricultural residues into useful energy carriers, as can be observed from Figure 2. Early studies primarily focused on the basic densification of agricultural residues, whereas recent investigations integrate physicochemical characterization, combustion analysis, and techno-economic evaluation. Mechanical durability and energy performance of briquettes depend strongly on factors such as moisture content, particle size distribution, binder type, and compaction pressure (Mani *et al.*, 2020; Obernberger and Thek, 2020). Technological improvements in briquetting machines and feedstock preparation methods have enhanced the quality and reliability of densified biomass fuels (Kaur and Singh, 2023).

Several studies have evaluated the physicochemical properties and combustion behaviour of briquettes produced from diverse biomass resources including agricultural residues, forestry wastes, and agro-industrial by-products (Garcia *et al.*, 2020; Mitchual *et al.*, 2020; Olorunnisola, 2021). Thermochemical conversion processes such as pyrolysis, torrefaction, and gasification also play a significant role in improving biomass fuel properties and enabling efficient energy recovery from lignocellulosic materials (Kumar *et al.*, 2020; Demirbaş, 2021).

Studies on pelletized and densified biomass fuels further emphasize the importance of feedstock composition and particle size distribution in determining fuel quality and combustion behaviour (Lehtikangas, 2020; Zhang *et al.*, 2020). Although significant progress has been made in understanding briquetting

technologies and densification processes, the quality and performance of briquettes ultimately depend on the characteristics of the biomass feedstocks used. Therefore, understanding the physicochemical properties of different biomass materials is essential for optimizing briquette production. The following section examines the characteristics of key feedstocks commonly used in briquette production. Recent studies indicate a steady increase in global research on biomass briquetting technologies due to growing interest in renewable energy and waste valorization, as illustrated in Figure 2.

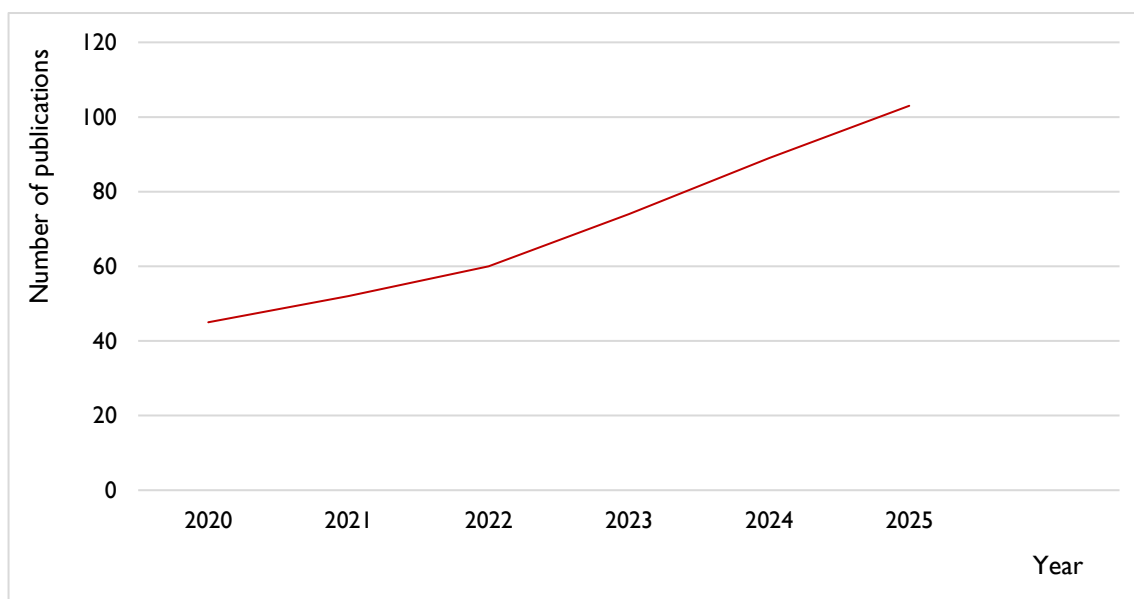


Figure 2. Global research trend in biomass briquetting studies between 2020 and 2025 showing increasing scientific attention toward densified biomass fuels

3.2 Feedstock Characteristics for Briquette Production

Rice husk is one of the most abundant agricultural residues generated from rice processing industries worldwide. Although rice husk contains moderate calorific value, its high silica content contributes to elevated ash levels (Saeed *et al.*, 2021). Sawdust, derived from wood processing industries, is widely used in briquette production because of its relatively high lignin content which acts as a natural binder during densification. Studies report calorific values ranging from 16–19 MJ/kg for sawdust briquettes (Nworie *et al.*, 2024; Alonge *et al.*, 2025).

Leaf biomass represents an emerging feedstock category in briquetting research. Although leaves typically exhibit lower calorific values compared with woody biomass, their higher volatile matter content improves ignition characteristics (Titi *et al.*, 2022). Black-currant (*Ribes nigrum*) leaves in particular have attracted recent scientific interest as a novel horticultural biomass feedstock. Suryajaya (2025) reported that black-currant leaves contain volatile matter in the range of 62–68%, which is considerably higher than that of rice husk (approximately 55–60%) and comparable to certain herbaceous biomass types. This elevated volatile fraction contributes to rapid ignition and shorter flame establishment times, making black-currant leaf biomass a potentially useful ignition-enhancing additive in composite briquette formulations. However, the relatively low lignin content of leaf biomass (typically below 15%) means that black-currant leaves cannot function effectively as a standalone briquetting feedstock without binder supplementation, and their hygroscopic tendencies may require careful moisture management during processing (Nworie *et al.*, 2024). The calorific value of black-currant leaf biomass is estimated at approximately 14–16 MJ/kg on a dry basis, which is lower than sawdust but sufficient to contribute meaningfully to composite blends when combined with higher-energy feedstocks.

The blending of different biomass materials is increasingly recognized as an effective strategy for optimizing briquette properties. Composite briquettes can balance ignition behaviour, combustion efficiency, ash content, and mechanical strength (Akowuah *et al.*, 2020; Sotannde *et al.*, 2021; Singh and Shukla, 2020). The physicochemical properties of biomass feedstocks strongly influence the combustion behaviour of briquettes produced from them. Parameters such as volatile matter content, ash composition, and lignin concentration directly affect ignition behaviour, burning rate, and heat release during combustion. Consequently, evaluating combustion performance is essential for assessing the practical suitability of biomass briquettes as household energy sources. Table I compares the properties of these feedstocks.

Table 1: Comparative physicochemical properties of rice husk, sawdust, and black-currant leaf biomass feedstocks used in briquette production

Parameter	Rice (Saeed et al., 2021)	Husk et al.,	Sawdust (Alonge et al., 2025)	Black-Currant Leaves and Thek (2020)
Calorific Value (MJ/kg)	12–15		16–19	14–16
Volatile Matter (%)	55–60		70–78	62–68
Ash Content (%)	15–25		0.5–3.0	5–10
Fixed Carbon (%)	12–20		16–22	10–18
Lignin Content (%)	5–8		20–30	<15
Moisture Content (%)	8–12		10–15	12–18
Silica/SiO ₂ Content (%)	87–97 (of ash)		Low	Low–Moderate
Binder Requirement	High		Low (self-binding)	High
Primary Advantage	High abundance; low cost		High energy; self-binding	High volatile matter; fast ignition

3.3 combustion Performance of Biomass Briquettes

Combustion performance is a critical parameter in evaluating the practical suitability of biomass briquettes for domestic and industrial energy applications. Key indicators include ignition time, burning rate, flame stability, thermal efficiency, and emission characteristics (Rahman et al., 2021; Zhang et al., 2021). Experimental studies indicate that well-designed briquettes can achieve thermal efficiencies ranging between 25–35% when used in improved cookstoves (Kpalo et al., 2022). In addition to combustion efficiency, emission characteristics such as carbon monoxide and particulate matter are important environmental considerations. Improved briquettes generally produce lower emissions compared with raw biomass fuels.

Table 2: Comparative combustion performance of selected biomass briquettes

Feedstock	Burning Rate (g/min)	Thermal Efficiency (%)	Ignition Behaviour	Reference
Rice Husk	2.8–3.2	25–30	Moderate	Saeed et al. (2021).
Sawdust	2.5–3.0	30–35	Stable	Kpalo et al. (2022);
Leaf Biomass	3.0–3.3	28–32	Fast	Yunusa et al. (2024);

Burning rate is influenced by volatile matter content, briquette density, and feedstock composition, which affect combustion stability and heat release during burning (Rahman et al., 2021; Zhang et al., 2021; Sotande et al., 2021). Thermal efficiency varies depending on briquette density, carbon content, and combustion behaviour during stove operation (Kpalo et al., 2022; Yunusa et al., 2024; Singh and Shukla, 2020).

While combustion testing provides practical insights into fuel performance, understanding the thermal degradation behaviour of biomass materials requires more detailed analytical techniques. Thermogravimetric analysis (TGA) has therefore become an important tool for studying the decomposition characteristics and kinetic behaviour of biomass fuels.

3.4 Thermogravimetric Analysis and Kinetic Behaviour

TGA is widely used to investigate the thermal degradation behaviour of biomass fuels. TGA provides valuable information on mass loss patterns and kinetic parameters during heating (Liu et al., 2021). Typical biomass degradation curves reveal three major stages: moisture evaporation below 150°C, devolatilization between approximately 200–400°C, and char oxidation at higher temperatures (Shen et al., 2020; Zhao et al., 2021). Activation energy values derived from TGA experiments provide insights into biomass reactivity and combustion behaviour. Studies report activation energies ranging between 160–250 kJ/mol for many agricultural residues. Thermogravimetric analysis of biomass materials typically reveals three major degradation stages including moisture evaporation, devolatilization, and char oxidation, as illustrated in Figure 3. Derivative thermogravimetric analysis further highlights the decomposition peaks corresponding to hemicellulose, cellulose, and lignin components of biomass materials as can be observed in Figure 4.

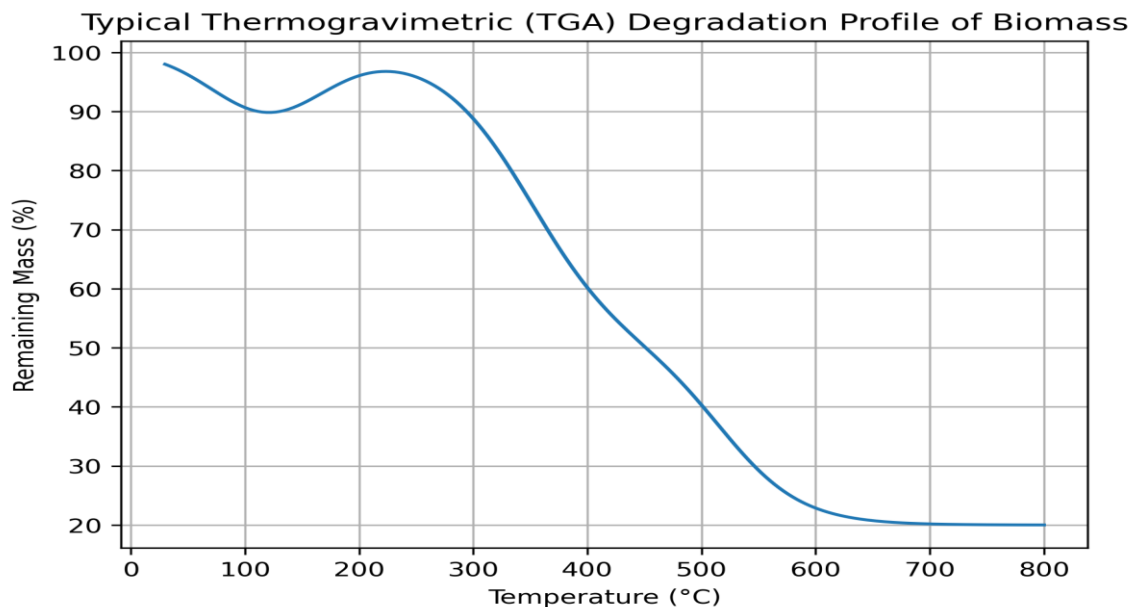


Figure 3: Typical thermogravimetric analysis (TGA) degradation profile of biomass materials showing the three main thermal decomposition stages: moisture evaporation, volatile matter release, and char oxidation (Shen *et al.*, 2020).

Derivative Thermogravimetric (DTG) Peak Analysis of Biomass Decomposition

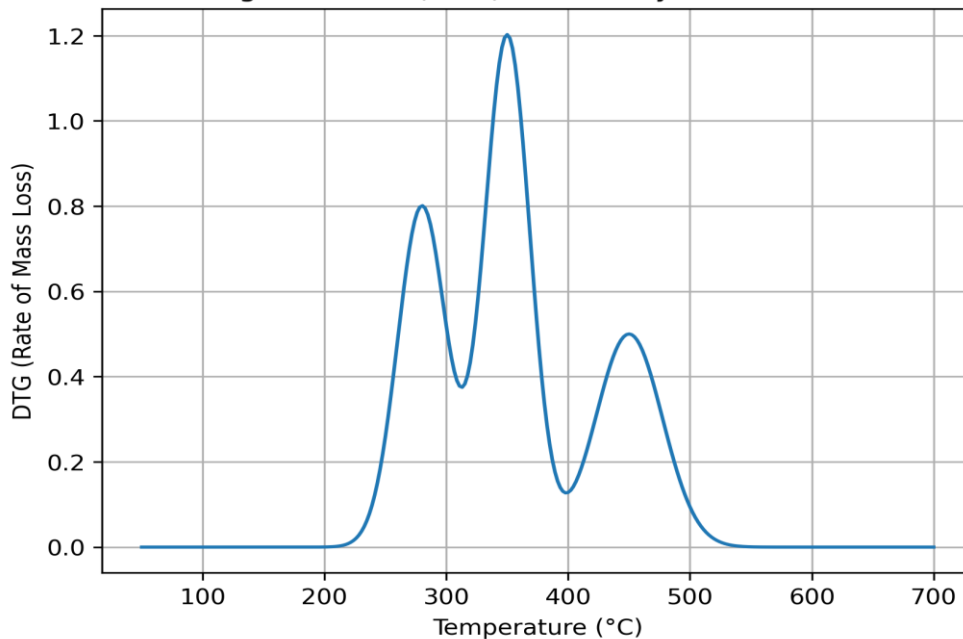


Figure 4: Derivative thermogravimetric (DTG) peak analysis showing major decomposition stages of biomass components including hemicellulose, cellulose, and lignin during thermal degradation (Zhao *et al.*, 2021).

3.5. Carbonization and Biomass Pre-Treatment

Carbonization is frequently applied as a pre-treatment method to improve biomass fuel properties. Thermal conversion processes such as pyrolysis and torrefaction increase carbon concentration and reduce volatile compounds (Basu, 2020; Mohan *et al.*, 2020).

Carbonized biomass typically exhibits higher calorific value, improved hydrophobicity, and enhanced storage stability compared with raw biomass (Chen *et al.*, 2020). For rice husk specifically, slow pyrolysis at temperatures between 400–500°C has been shown to increase calorific value from approximately 14 MJ/kg (raw) to 18–22 MJ/kg (carbonized), while reducing ash content through partial removal of silica volatiles (Lubwama and Yiga, 2024). Torrefaction of sawdust at 250–300°C similarly improves energy density by 10–20% while reducing the oxygen-to-carbon ratio, which enhances hydrophobicity and reduces susceptibility to biological degradation during storage (Oginni *et al.*, 2022). For black-currant leaf biomass, carbonization is particularly relevant given the high volatile content of raw leaves, which can cause excessive smoke

generation during combustion; carbonized leaf char would likely exhibit more stable and cleaner burning characteristics, although experimental data specifically for black-currant leaf char briquettes remain unavailable in the current literature. Yiga *et al.* (2023) demonstrated that carbonized agricultural briquettes produced from comparable herbaceous feedstocks achieved thermal efficiencies 12–18% higher than their non-carbonized equivalents when tested in improved cookstoves, underscoring the practical value of pre-treatment for leaf-based briquette formulations.

3.6 Techno-Economic Feasibility of Briquette Production

Techno-economic assessments indicate that biomass briquette enterprises can provide sustainable income opportunities while contributing to renewable energy development. Studies have demonstrated that small-scale briquette production units can achieve favourable economic returns when locally available feedstock and simple briquetting technologies are used (Tripathi *et al.*, 2020; Kpalo *et al.*, 2022).

International development organizations have also recognized biomass briquetting as an important strategy for improving rural energy access and supporting sustainable livelihoods (UNDP, 2022). Tripathi *et al.* (2020) reported production costs for small-scale rice husk briquettes in India ranging from USD 30–55 per tonne, compared with market selling prices of USD 70–100 per tonne, suggesting gross margins of approximately 40–50% under favourable feedstock availability conditions. Kpalo *et al.* (2022) similarly estimated that a small briquette enterprise operating at 500 kg/day capacity in sub-Saharan Africa could achieve payback periods of 12–24 months depending on equipment costs, local fuel prices, and feedstock supply reliability. However, these estimates are sensitive to feedstock procurement costs, which can vary substantially based on proximity to agricultural processing sites. For composite briquette enterprises incorporating leaf biomass such as black-currant leaves, feedstock collection costs may be lower given that leaves are often available as zero-cost agricultural waste, though additional drying and particle size reduction requirements may offset this advantage. A comprehensive techno-economic model specifically evaluating composite rice husk–sawdust–black-currant leaf briquette enterprises remains absent from the literature and represents a priority area for future investigation.

4. Research Gaps and Future Research Directions

Despite the growing body of literature on biomass briquetting technologies, several important research gaps remain. First, most existing studies focus primarily on conventional feedstocks such as rice husk and sawdust due to their widespread availability and favorable lignocellulosic composition (Kpalo *et al.*, 2020; Jain *et al.*, 2022). However, the potential of horticultural biomass residues, particularly leaf-based materials such as black-currant leaves, has received comparatively limited attention. Exploring alternative biomass resources is essential for expanding feedstock diversification and improving resource utilization.

Second, many investigations evaluate individual performance parameters such as calorific value, ash content, or mechanical strength without integrating these characteristics within a comprehensive framework that includes combustion behaviour, thermal degradation kinetics, and techno-economic feasibility. Although literature exists on this, the relationship between laboratory-scale characterization and real-world stove performance remains insufficiently understood (Liu *et al.*, 2021; Shen *et al.*, 2020). Third, although composite briquettes have been shown to improve fuel performance by balancing ignition behaviour and mechanical durability, systematic optimization of multi-feedstock briquette formulations remains limited in the literature.

5. Conclusion

Biomass briquettes produced from rice husk, sawdust, and black-currant leaves exhibit distinct and complementary performance characteristics based on key physicochemical and combustion parameters. Sawdust demonstrates superior fuel quality with calorific values of 16–19 MJ/kg and low ash content (0.5–3%), resulting in higher thermal efficiency (30–35%). In contrast, rice husk shows high ash content (15–25%) due to silica, which limits combustion efficiency despite its abundance. Black-currant leaves exhibit high volatile matter (62–68%), enabling rapid ignition but requiring binder support due to low lignin content. Thermogravimetric analysis confirms three-stage degradation behaviour, with activation energy values ranging from 160–250 kJ/mol, indicating moderate thermal stability across the feedstocks. Composite briquettes provide improved performance by balancing ignition, combustion stability, and mechanical strength compared to single-feedstock briquettes.

However, the review reveals critical gaps. There is no optimized blending ratio for these three feedstocks, limited experimental data on black-currant leaf briquettes, and a lack of integrated techno-economic models. Future research should focus on (i) optimization of composite formulations, (ii) experimental validation of combustion and emission performance, and (iii) development of location-specific techno-economic models to support large-scale deployment.

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