

Review

Bio-Coal Briquetting as a Potential Sustainable Valorization Strategy for Fine Coal: A South African Perspective in a Global Context

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Abstract

The generation of fine coal particles during mining and processing presents significant environmental and logistical challenges, particularly in coal-dependent, developing countries like South Africa (SA). This review critically evaluates the technical viability of fine coal briquetting as a sustainable waste-to-energy solution within a SA context, while drawing from global best practices and comparative benchmarks. It examines abundant feedstocks that can be used for valorization strategies, including fine coal and agricultural biomass residues. Furthermore, binder types, manufacturing parameters, and quality optimization strategies that influence briquette performance are assessed. The co-densification of fine coal with biomass offers a means to enhance combustion efficiency, reduce dust emissions, and convert low-value waste into a high-calorific, manageable fuel. Attention is also given to briquette testing standards (i.e., South African Bureau of Standards, ASTM International, and International Organization of Standardization) and end-use applications across domestic, industrial, and off-grid settings. Moreover, the review explores socio-economic implications, including rural job creation, energy poverty alleviation, and the potential role of briquetting in SA's 'Just Energy Transition' (JET). This paper uniquely integrates technical analysis with policy relevance, rural energy needs, and practical challenges specific to South Africa, while offering a structured framework for bio-coal briquetting adoption in developing countries. While technical and economic barriers remain, such as binder costs and feedstock variability, the integration of briquetting into circular economy frameworks represents a promising path toward cleaner, decentralized energy and coal waste valorization.

Keywords: coal briquettes; fine coal; binders; biomass; bioenergy; waste valorization



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1. Introduction

The rapid industrialization and urbanization of developing nations have significantly increased global energy demand, driving continued reliance on non-renewable sources such as petroleum, natural gas, and coal [1]. In SA, coal remains the primary energy source,

supplying around 72% of total energy needs as of 2023, despite a global decline in coal dependency from 29% to 26% over the past decade [1,2]. Coal supports several key sectors in SA (Figure 1), with 53% used for electricity generation, 33% for petrochemicals (mainly by SASOL), 12% in metallurgy, and 2% for domestic use. While global usage trends share some similarities, notable differences exist; for instance, electricity generation globally accounts for 68% of coal use, significantly higher than SA's 53%, and most countries do not rely on coal for petrochemical production to the extent seen in SA.

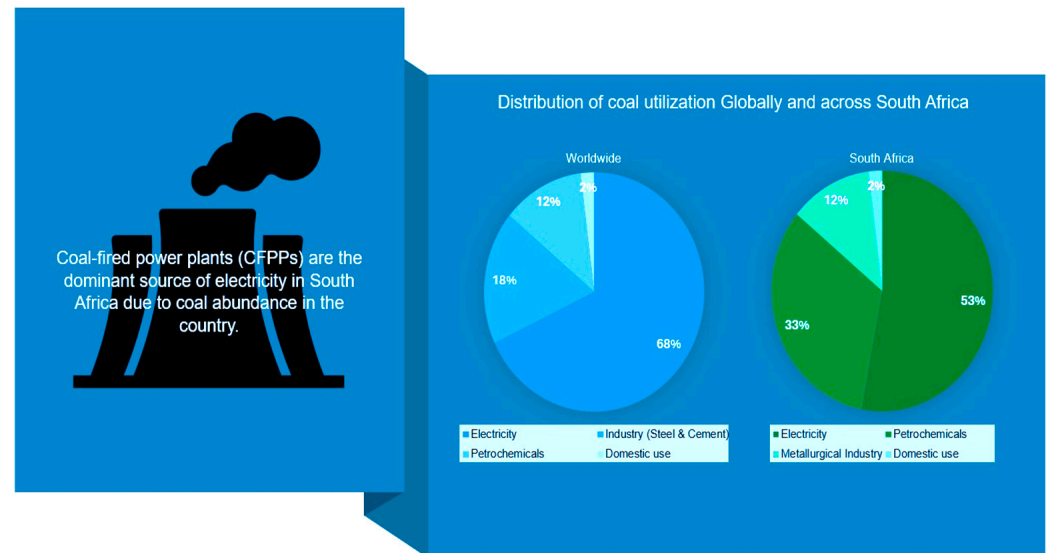


Figure 1. Percentage distribution of coal utilization across major economic sectors in South Africa (2023) compared to global sectoral coal consumption [1–3].

Despite coal's continued dominance, SA's energy system remains deeply flawed and unequal. According to the 2021 General Household Survey, 11% of households, mostly in rural areas, lack grid access [4]. Those with access face frequent outages due to aging infrastructure and a post-pandemic 11.2% drop in coal output [5], leading to persistent load shedding by the local Electricity Supply Commission, ESKOM [6]. The International Energy Agency (IEA) forecasts a 3.4% annual rise in energy demand through 2026, worsening this crisis [1]. Furthermore, environmental concerns compound the issue. South Africa generates approximately 60 million tons of sulfur-rich coal mine waste (CMW) annually, stored across more than 200 active tailing dams [7]. Of this, fine coal accounts for an estimated ~10 million tons per year based on beneficiation losses reported in large-scale washing plants and historical production assessments [7–9]. Fine coal refers to coal particles smaller than 2 mm. Although some literature distinguishes 'ultrafine coal' as particles below 150 μm , this review uses 'fine coal' as an umbrella term to encompass both fine and ultrafine fractions relevant to briquetting applications. The fine coal contains high ash (~45%), moisture (~25 wt.%), and sulfur (~5%), making it unfit for direct use [9,10]. Improper disposal poses serious environmental and health risks.

Nonetheless, coal will remain central to SA's energy mix due to its abundance and affordability. Progress in renewables has been slow, hindered by infrastructure gaps and policy delays [6,11]. As a result, attention is shifting toward sustainable, circular solutions that improve coal's environmental and economic footprint. One such strategy is the co-condensification or briquetting of fine coal with biomass. This process compresses fine coal and biomass into dense, easy-to-handle briquettes with lower emissions and higher energy density, termed bio-coal briquettes [12]. Binders such as molasses, starch, or gum Arabic, often sourced locally, are used to enhance briquette strength and cohesion [13,14]. Bio-coal briquettes can offer rural communities a cleaner, low-smoke alternative to traditional

fuels like firewood or dung cakes and may also serve in the agriculture and construction sectors [15–17]. Given their local production potential and broad applicability, further research is needed to optimize the process for decentralized, low-cost energy delivery.

This review provides a SA-focused analysis of bio-coal briquetting, supported by a global body of literature to ensure technical relevance and contextual depth. It explores the technical viability of bio-coal briquetting in a global context, with the aim of enhancing its applicability and implementation in developing countries such as Africa, in general, and more specifically, SA. The focus is on feedstocks, binder selection, process parameters, and implementation challenges. It highlights how this technology can contribute to sustainable energy access, waste valorization, and economic diversification, particularly in rural and underserved regions.

2. Valorization Strategies of Fine Coal

2.1. Sources and Characteristics of Fine Coal

Fine coal is a byproduct generated during various stages of coal mining, handling, and processing operations. It typically consists of coal particles smaller than 2 mm in diameter, although in some contexts, the classification extends to particles under 5 mm [17,18]. In Figure 2, the primary sources of fine coal, i.e., (a) mining, (b) coal preparation (crushing and screening), (c) beneficiation waste, and (d) stockpiles and weathering, are highlighted. Across these sources, the composition of fine coal is heterogeneous and often influenced by geological origin, mining techniques, and beneficiation processes [18–20]. It is typically composed of high ash (~45%) and moisture content (HHV) (up to 25%), and often, elevated sulfur and trace metals [21–23]. Its low higher heating value, low bulk density, and high surface area impede combustion and handling, necessitating valorization approaches such as briquetting.

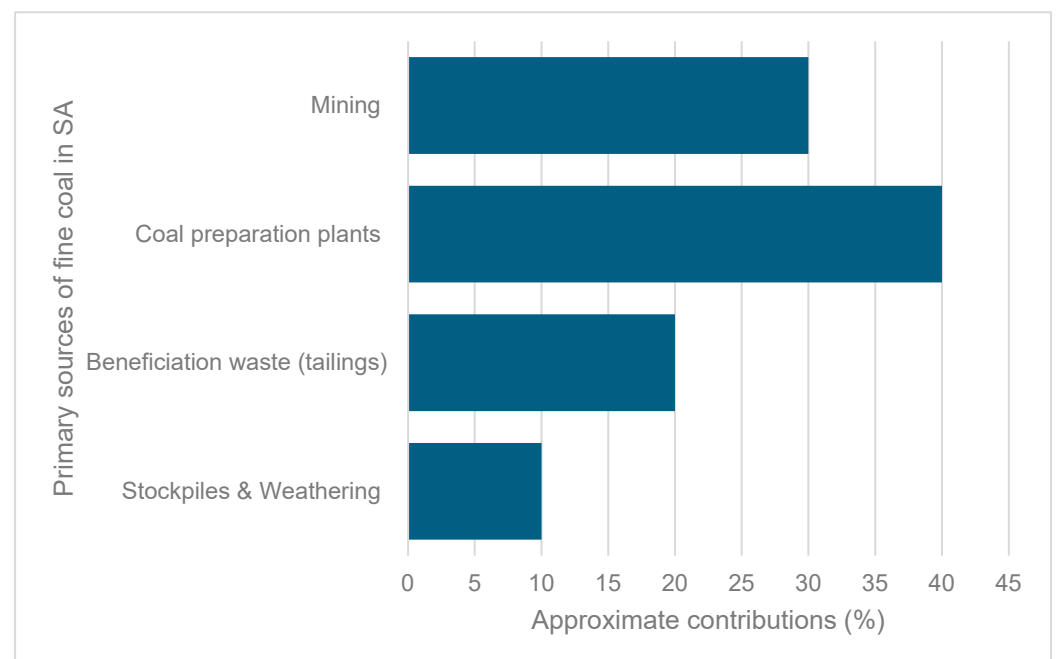


Figure 2. Estimated contributions of key operations to fine coal generation across the coal production chain in South Africa [1,20–26].

- (a) Mining: Fine coal is initially generated during mining operations, particularly in underground settings. Mechanical actions such as blasting, cutting, and continuous extraction break coal into smaller particles [22,23]. SA coals, being friable, are especially prone to fragmentation during these processes [20,21].

- (b) Coal Preparation (Crushing and Screening): Crushing and screening operations further contribute to fines generation due to particle abrasion and breakage [27]. High-speed crushers and dry screening are particularly associated with increased fines, with equipment type and operational settings playing a significant role [22,27,28].
- (c) Beneficiation waste: Processes like dense medium separation, spirals, and flotation generate ultrafine particles through attrition and turbulence [22,25,28]. These fines are often unrecovered, ending up in slurry ponds or tailings, representing a major inefficiency in coal beneficiation [24,29,30].
- (d) Stockpiles and weathering: Storage and handling exacerbate fines formation as coal degrades due to compaction, oxidation, and environmental exposure [20,25]. Weathering from rain, wind, temperature changes, and microbial activity further fragments the coal, especially when stockpiles are unprotected [20,29].

2.2. The Necessity of Developing Valorization Strategies for Fine Coal

Globally, the coal industry faces mounting pressure to adopt sustainable and circular waste management practices, particularly for fine coal, which is often stored in tailing dams. These storage methods pose significant environmental risks, as evidenced by catastrophic failures at Mount Polley (Canada, 2014), Bento Rodrigues (Brazil, 2015), and Brumadinho (Brazil, 2019) [30–33]. In response, organizations like the International Council on Mining and Metals (ICMM) now emphasize waste minimization through valorization [24].

In SA, where coal remains a critical energy source, the urgency is heightened. The 2022 Jagersfontein tailing dam collapse caused fatalities and property loss, illustrating the dangers of long-term fine coal storage [34]. At the same time, the country's deepening energy crisis, characterized by frequent blackouts and unreliable grid access, leaves many rural communities dependent on polluting fuels such as firewood, dung, and coal dust [35,36]. Valorizing fine coal into useful products like briquettes addresses both challenges: reducing environmental hazards and delivering cleaner, decentralized energy. As global momentum shifts toward sustainable mining, SA must prioritize fine coal valorization as a strategic environmental and socio-economic intervention.

In SA, briquetting is gaining traction as a key valorization strategy. The Council for Scientific and Industrial Research (CSIR), as well as other collaborators (Coaltech), have been exploring waterless coal beneficiation, including briquetting, to improve fine coal usability for more than a decade [21,25,26]. Additionally, SASOL has partnered with EESTech Inc.© (Brisbane, Australia) to develop briquetting solutions for surplus fine coal [37]. These efforts reflect growing national interest in briquetting as a sustainable pathway for coal waste management. Among the various fine coal valorization strategies, briquetting emerges as particularly well-suited for SA. With abundant fine coal waste and a growing need for affordable, cleaner-burning solid fuels, briquetting offers a practical, scalable, and relatively low-cost solution. Unlike other technologies that require complex infrastructure or face adoption barriers, briquetting is adaptable for both industrial and domestic use. Its ability to convert fine coal into compact, transportable, and cleaner-burning briquettes makes it a strong candidate for widespread application.

Despite the growing interest, no prior review has comprehensively analyzed the full technical, environmental, and policy dimensions of fine coal briquetting specifically tailored to SA's conditions. This review is, therefore, novel in its integrated approach, merging feedstock and binder optimization with local implementation strategies aligned to national goals such as the JET and decentralized energy access. Thus, the remainder of this review will focus on examining the technical viability of briquetting in SA, including manufacturing methods; feedstocks; binders; quality testing; applications; and its potential to address the country's energy, environmental, and socio-economic challenges.

3. Technical Viability of Fine Coal Briquetting in South Africa

3.1. Briquetting Process

Briquetting is a key densification technique that can convert fine particulate materials such as fine coal or biomass residues into compact, solid briquettes with enhanced handling, combustion, and transport characteristics. The process typically consists of several integrated stages: size reduction (crushing), mixing (biomass–binder–fine coal), densification, drying, and packaging, as illustrated in the simplified process flow diagram (Figure 3).

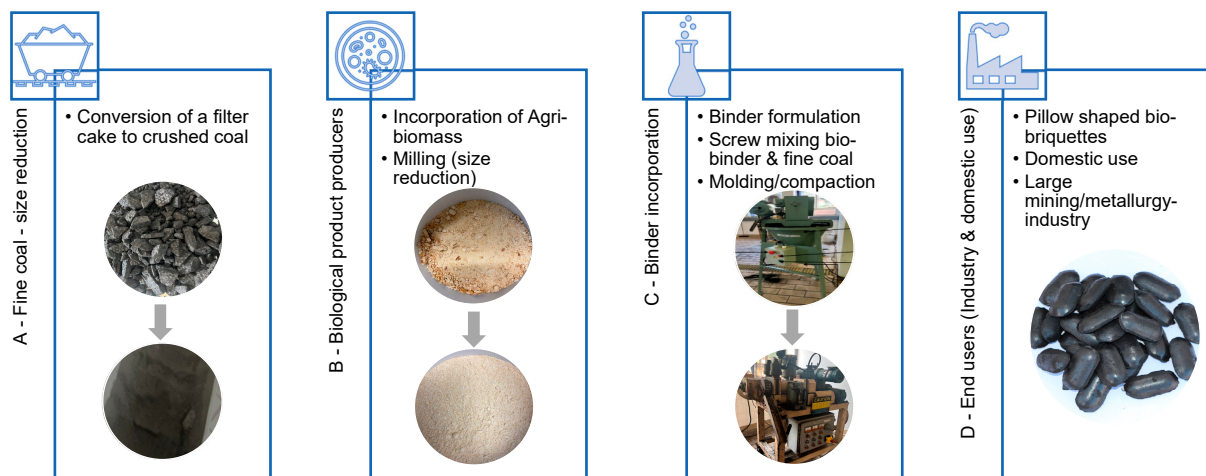


Figure 3. Process flow of bio-coal briquetting using a binder, showing key steps: fine coal and biomass preparation, binder formulation, mixing, briquetting, curing, and final packaging [38–42].

In the presented scheme, raw coal in the form of filter cake from coal preparation plants is first subjected to mechanical crushing, reducing its particle size to uniformly fine coal with improved surface area and packing density suitable for briquetting. Simultaneously, a binder formulation, which may include organic, inorganic, or green biobinders (as in this illustration), is prepared and fed into a screw mixer, where it is homogenized with the fine coal. Proper mixing ensures uniform binder distribution, which is essential for achieving consistent briquette strength and quality [38,39]. This uniform mixture is then transferred to a coal briquetting machine, which applies pressure to form compact briquettes of the desired shape and size. During this stage, physical bonding and chemical interactions between particles occur, forming briquettes with a defined shape and size [40–42]. The freshly formed briquettes are passed through a drying and curing stage, which helps to remove excess moisture and enhance structural stability [41]. Proper drying is crucial to avoid microbial degradation, improve storage life, and ensure clean combustion [20,29,42]. Finally, the dry briquettes are transferred for storage and packaging, ready for transport, distribution, or end-use application. This process can be tailored depending on the feedstock characteristics, intended end-use, and type of binder applied. In the SA context, the ability to adapt this process using efficient briquetting technologies and locally available feedstocks and binders presents significant opportunities for sustainable energy development and fine coal valorization.

3.2. Methods of Briquetting

Briquette compaction methods are central to determining the efficiency, durability, and combustion performance of solid fuels derived from fine coal and biomass [39,42]. These technologies vary in operational parameters, product characteristics, and suitability for different feedstocks. Primary briquetting methods include (a) mechanical densification, (b) piston press, (c) screw extrusion, and (d) roll press compaction. Each offering distinct

technical and economic trade-offs, discussed below, with conclusions made relevant to the SA context.

- (a) Mechanical densification compresses loose materials like sawdust, rice husks, groundnut shells, and fine coal into dense, transportable briquettes using pressure with or without heat [43–46]. This improves bulk density, reduces MC, and enhances handling [45,46]. Heated systems activate thermoplastic components like lignin, enabling binderless briquetting with improved strength [47]. Although energy-intensive, the method produces durable briquettes with high combustion efficiency [44].
- (b) Piston press technology is widely adopted in developing countries due to its low cost, simplicity, and adaptability to various biomass types [39,48]. A reciprocating piston compresses dry, fibrous feedstock such as straw and husks inside a die, generating frictional heat that softens lignin to act as a natural binder [48]. The result is dense, cylindrical briquettes suitable for domestic heating and cooking [39,43,49]. Efficient operation requires uniform particle size and low MC to minimize wear and maintain quality.
- (c) Screw extrusion involves feeding biomass through a rotating screw into a heated die, compressing it under high pressure and temperature (150–300 °C) [39,43,48]. This partial carbonization improves combustion properties and lowers volatile content [48]. Notably, high-quality briquettes can be produced without binders, as demonstrated by Sundar et al. [48], who achieved a higher heating value (HHV) of 16.73 MJ/kg. The resulting briquettes often have a central hole that enhances airflow and combustion efficiency, making them ideal for clean cooking stoves. However, screw extruders are mechanically complex and maintenance-intensive, limiting their suitability for low-resource environments.
- (d) Roller press briquetting involves feeding fine material between two counter-rotating rollers equipped with small dies of ~30 mm [39,50]. This method is prevalent in industrial applications involving uniform, fine materials like fine coal [39,43]. It accommodates a variety of binders to enhance strength and moisture resistance, offering high throughput, making it suitable for continuous processing lines [42]. However, it demands the pre-conditioning of feedstocks, including precise moisture control and particle size reduction, to ensure consistent briquette quality [39,50].

Each of these technologies influences the final briquette's structure, HHV, MC, and combustion profile [39]. In the SA context, the country is characterized by plentiful fine coal, biomass residues, and varied energy demands. Hence, the choice of briquetting technology must balance technical performance with cost and scalability. For rural and off-grid communities, piston press briquetting stands out due to its low maintenance needs, affordability, and compatibility with locally available feedstocks. When paired with natural binders such as starch or microbial agents, it can produce clean-burning briquettes suitable for heating, cooking, and decentralized electrification [51,52].

Conversely, for industrial-scale operations like those at SASOL, roll press compaction is more appropriate. Its capacity for continuous production, binder flexibility, and structural precision makes it ideal for integration into advanced thermochemical systems, including gasification and pyrolysis [39,42,50]. Ultimately, the choice of briquetting method depends on feedstock properties, end-use requirements, and local infrastructure. Each of these offers unique opportunities for valorizing SA's fine coal in a sustainable, economically viable manner.

3.3. Potential Feedstocks Used for Briquetting

The successful implementation of briquetting technologies in SA depends largely on the nature and quality of locally available feedstocks. Co-densified briquetting, where fine

coal is blended with biomass, offers a particularly compelling opportunity in the SA context due to the country's simultaneous abundance of fine coal and lignocellulosic residues. Understanding the properties, availability, and suitability of these feedstocks is essential for designing briquetting systems that are both technically viable and socioeconomically aligned with national needs.

3.3.1. Properties of South African Fine Coal

South Africa, a top global coal producer, generates over 250 million tonnes of coal annually, with ~60 million tonnes discarded, ~10 million tonnes of which is fine coal [53–55]. Typically stored in slurry ponds or tailing dams, these fines pose environmental risks such as leaching, dust, and spontaneous combustion [30]. Despite being treated as waste, fine coal retains substantial energy value (8–24 MJ/kg) [54], making it a promising feedstock for briquetting, especially when co-processed with biomass to improve binding and combustion properties [20]. These fines come from anthracite, bituminous, sub-bituminous, and lignite coals (Table 1), with SA national availability estimated at 20%, 15%, 10% and <5%, respectively [55–57].

Table 1. Availability and suitability of fine coal for briquetting in South Africa.

Coal Type	Fine Coal Generation (% of Total)	Size Range	Typical Uses	Processing Methods	Raw Coal HHV (MJ/kg)	Fine Coal HHV (MJ/kg)	Suitability for Briquetting	References
Anthracite	~20%	<6 mm (fines); <0.15 mm (ultrafines)	Reductants, filtration, and domestic heating	Screening, drying, and briquetting	30–33	20–25	High—low moisture; strong structure	[1,58,59]
Bituminous	~15%	0.15 mm–6 mm; <0.15 mm	Power gen., export, cement kilns, and industrial boilers	Dense medium cyclones, spirals, flotation, and dewatering	24–30	17–24	High—commonly briquetted globally	[1,25,56]
Sub-bituminous	~10%	0.15 mm–6 mm; <0.15 mm	Power generation (Eskom) and synthetic fuels (Sasol)	Screening, flotation, and drying	18–23	15–20	Moderate—needs additives/drying	[1,2,56]
Lignite	<5%	<6 mm; <0.15 mm	Low-grade fuel (limited economic use)	Minimal processing	10–18	8–14	Low—high moisture, poor binding	[1,57]

Bituminous fine coal is best suited for binderless briquetting due to higher volatile matter (VM) and thermal plasticity [21,25,56]. Conversely, sub-bituminous and lignite fines have lower energy content, higher MC, and poor cohesion, requiring strong binders [53,57]. Anthracite, though rich in fixed carbon, lacks agglomeration properties, often necessitating additives or blending with biomass [25,58,59]. Optimizing briquette performance requires tailored feedstock selection and densification strategies aligned with these specific coal types.

3.3.2. Biomass Residue Availability and Suitability

South Africa also has an abundant and diverse biomass base, much of which remains underutilized or unmanaged. According to the Department of Forestry, Fisheries and the Environment (DFFE), the country produces over 30 million tonnes of agricultural and forestry residues annually [60]. These biomass residues, if properly harnessed, could be redirected from burning or decay toward sustainable energy production via briquetting. Table 2 presents common biomass types that have been utilized in various co-densification strategies and their suitability for co-densification with fine coal.

Table 2. Availability and suitability of feedstocks for briquetting in South Africa.

Biomass Type	Source Regions	Availability (Est.)	Suitability	Physiochemical Characteristics	References
Sawdust and wood chips	Mpumalanga, Eastern Cape, and KwaZulu-Natal	>440 kilotonnes/annum	High heating value; low ash.	Moisture: 10–50% Higher Heating Value: 16–20 MJ/kg Mineral content: 1–3% Bulk density: 160–190 kg/m ³	[61–63]
Bagasse	KwaZulu-Natal and Mpumalanga	>7 million kilotonnes/annum	Readily available from sugar mills.	Moisture: 45–55% Higher Heating Value: 15–19 MJ/kg Mineral content: 1–3% Bulk density: 150–300 kg/m ³	[63–66]
Wheat/maize straw	Free State, North West, and Gauteng	>600 tonnes/annum	Fibrous; good structural filler.	Moisture: 10–15% Higher Heating Value: 13–15 MJ/kg Mineral content: 5–8% Bulk density: 80–120 kg/m ³	[63,67]
Sunflower husks	North West and Limpopo	~733 kilotonnes/annum	Good blend with coal fines.	Moisture: 8–12% Higher Heating Value: 16–18 MJ/kg Mineral content: 2–3% Bulk density: 160–200 kg/m ³	[68,69]
Corn cobs/Stalks	Free State, North West, and Limpopo	>8 million tonnes/annum	Improves combustion efficiency.	Moisture: 12–20% Higher Heating Value: 14–16 MJ/kg Mineral content: 2–4% Bulk density: 180–220 kg/m ³	[63,66]
Macadamia shells	Mpumalanga and Limpopo	~68 kilotonnes/annum	High energy density; low sulfur.	Moisture: 6–10% Higher Heating Value: 18–20 MJ/kg Mineral content: <1% Bulk density: 350–450 kg/m ³	[70,71]
Alien invasive biomass—black wattle	National (Working for Water program)	~130 kilo-hectars (commercial)	Ecological benefit + fuel value.	Moisture: 15–35% Higher Heating Value: 16–19 MJ/kg Mineral content: 1–3% Bulk density: 200–300 kg/m ³	[72–74]

The following biomass residues are particularly promising for blending with fine coal in SA, based on their availability, proximity to coal mining operations, and physicochemical compatibility:

- (a) **Sawdust and wood chips:** It is generated in abundance by the SA commercial forestry sector and sawmills, particularly in Mpumalanga and KwaZulu-Natal, the same provinces where coal mining is concentrated, reducing logistics costs [1,2]. It offers high carbon content and low sulfur, and has been shown to contribute to briquette structural integrity [61,62]. Manyushi et al. [20] produced briquettes with improved HHV (25–26 MJ/Kg) when blending sawdust with fine coal and molasses as binder. However, the high MC variability (10–50%) may necessitate pre-drying or moisture control to ensure briquette consistency.
- (b) **Bagasse:** A fibrous byproduct of sugarcane processing, produced in sugar mills, especially in KwaZulu-Natal. Bagasse has good energy content and blends well with fine coal [63]. According to Costa et al. [75], the HHV ranges between 15 and 18 MJ/kg. Bagasse is a year-round residue and often treated as waste, offering high potential for circular economy value [63,65]. Despite this, bagasse's high initial MC (45–55%) requires drying or blending with lower-MC materials to prevent poor briquette stability.
- (c) **Wheat Straw:** A fibrous byproduct of wheat grain cultivation, wheat straw is abundant in the Western Cape and Free State provinces of SA. Although it is naturally low in density, its briquetting performance can be enhanced through pre-treatment methods such as chopping or pelletizing [63,67]. Due to its lignocellulosic composition, wheat straw not only blends well with fine coal but also serves as an effective natural binder [63,76]. According to Kumar et al. [77], incorporating wheat straw into fine ash coal improves both the ignition index (2.81 to 5.14 mass²/min² °C³) and the overall combustion index (3.58 to 8.11 mass/min² °C³). Nevertheless, its low bulk

density (80–120 kg/m³) poses challenges for cost-effective transport and storage unless pre-compacted

- (d) Sunflower husks: A byproduct of oilseed processing that remains when the seeds are taken out. In SA, it is readily available in the Free State and Northwest provinces. Characterized with relatively low mineral content (2–3%) and moderate HHV (16–18 MJ/kg), it makes excellent biomass partners for blending with fine coal, especially for rural or agro-industrial zones [68,69]. Nikiforov et al. [78] recently showed that a percent ratio of 70/30% of sunflower husks and fine coal dust yielded the best combination of strength (80.95%), density (901.48 kg/m³), and HHV (21.33 MJ/Kg). However, their loose structure can affect briquette density and integrity, often requiring stronger binders or higher compaction pressures
- (e) Corn Cobs/stalks: The remaining hard core of maize. Corn is SA's most cultivated crop with 16 million tonnes produced in 2024/25 [63,66]. The cobs generated from this offer good structural properties for briquettes and moderate HHV (14–16 MJ/kg) [66]. Their porous nature supports efficient combustion, while their seasonal abundance allows for storage and batch processing. Lu et al. [79] showed that corn stalks blending with fine coal improved briquette quality, with compressive strength increasing by 3.33 MPa. Still, their seasonal availability may result in inconsistent feedstock supply, necessitating stockpiling and drying facilities.
- (f) Macadamia shells: Hard and tough shells are generated during the production of macadamia nuts. In SA, it is primarily produced in Limpopo and Mpumalanga provinces [70]. The shells are high in fixed carbon and dense, yielding durable briquettes with moderate HHV (18–20 MJ/kg) [71]. Thermogravimetric analysis studies conducted by Bada et al. [80] showed that the co-firing of macadamia shells with coal in various ratios (20/80, 50/50, and 80/20%) all resulted in higher reactivity than coal alone. Additionally, this co-firing has found local commercial application, with the company SHISA-Eco briquettes©, which claims to produce a blended briquette product with 80% less fine particles and 75% less carbon monoxide. Yet, their hardness may cause excessive wear on briquetting equipment, often requiring pre-crushing and screening.
- (g) Invasive biomass (i.e., black wattle): These are actively removed in ecological restoration projects and offer a dual benefit: restoring native ecosystems and providing bioenergy feedstock. The Working for Water program identifies over 10 million tonnes of potential biomass annually from alien species alone [72,74]. Additionally, the country allows the commercial production of ~130 kilo-hectars of black wattle [72–74]. Although studies on the co-densification of wattle with fine coal are limited, its high lignin content, low ash yield, and widespread availability in SA present a significant opportunity for efficient and sustainable briquette production. However, inconsistent harvesting cycles and the lack of established supply chains may limit scalable and year-round availability.

Comparatively, sawdust and macadamia shells exhibit the highest energy content and combustion efficiency, making them ideal for urban and industrial applications. Bagasse and corn cobs, while moderate in HHV content, offer strong binding potential due to their fibrous structure, which could ease rural briquette production with minimal binder use. Conversely, wheat straw and sunflower husks, though abundant, may require binder enhancement or densification pre-treatments to achieve mechanical durability and moisture resistance in humid climates. These differences should inform feedstock selection based on briquette application and geographic location.

These biomass types are not only geographically and economically suitable but also chemically compatible with fine coal, making them strong candidates for integration

in local waste-to-energy systems. Sawdust, corn cobs, bagasse, and invasive species biomass are particularly well-suited as feedstocks for blending with fine coal due to their HHV, high local availability, and low-cost accessibility. Utilizing these materials not only addresses pressing energy security and waste management issues but also aligns with national strategies for green industrialization and climate-smart development [81]. The integration potential of fine coal and biomass residues into co-briquetted fuels addresses key national priorities such as energy access, waste valorization, job creation, and climate-smart development [11,81]. Such strategies align with SA's Green Economy Strategy and Industrial Policy Action Plan (IPAP), offering localized energy solutions that reduce dependence on fossil fuels and open new avenues for rural industrialization [82].

The effectiveness of bio-coal briquettes depends not only on the inherent properties of the coal and biomass feedstocks, but also on the choice and compatibility of binders used. The interaction between these materials plays a key role in determining the briquette's structural strength, combustion efficiency, and resistance to degradation during storage and transport. For example, fibrous or low-lignin biomass types may require stronger external binders to compensate for weak self-binding capacity, while some high-starch or lignocellulosic residues may partially self-bind under pressure. The following section explores various binder types and their specific roles in enhancing briquette performance, with a focus on those relevant to SA conditions.

3.4. Binders in Fine Coal Briquetting

Binders are integral to the briquetting process, especially in the densification of fine coal and biomass mixtures. It plays a critical role in improving the mechanical integrity, thermal properties, and storage stability of the final briquettes. This section presents a detailed overview of the mechanisms by which binders facilitate bonding, followed by a classification of binder types, including organic, inorganic, synthetic, and emerging green biobinder options, and concludes with guidelines for binder selection relevant to the SA context.

3.4.1. Binding Mechanism

The mechanism of binding in the briquetting process is governed by a combination of mechanical pressure, particle rearrangement, binder chemistry, and moisture dynamics, all contributing to the formation of durable briquettes. According to Zhang et al. [12], primary bonding mechanisms include mechanical interlocking, solid bridge formation, and intermolecular attractions such as Van der Waals forces and hydrogen bonding. Under sufficient pressure, particles deform and reposition to create a dense matrix, while binders fill gaps and promote adhesion between surfaces [12,83]. Butler et al. [84] note that this contact is particularly enhanced in the presence of moisture, which helps mobilize and activate water-soluble or gelatinizing binders such as starch or molasses, thereby improving bond formation.

Additionally, Oladeji [85] notes that during densification, especially under elevated pressure and temperature, natural binders such as lignin can be softened or released from biomass and re-solidified upon cooling, contributing to structural integrity through thermoplastic bonding. Similarly, Tumuluru et al. [86] highlight that diffusion and capillary forces may also contribute to particle cohesion in fine materials, while chemical reactions, particularly in the presence of reactive additives, can form cementitious bonds that enhance stability, especially in systems employing inorganic binders.

For optimal performance, it is important to recognize that binder effectiveness is significantly influenced by process variables such as binder concentration, particle size distribution, MC, and compaction pressure [12,84,87]. Tumuluru et al. [86] further highlight

that plastic deformation and the viscoelastic behavior of biomass particles under sustained pressure play a vital role in densification, particularly for lignocellulosic feedstocks. Ultimately, the interplay of these physical and chemical mechanisms governs the mechanical strength, durability, water resistance, and combustion characteristics of the final briquette product. Given this complexity, careful selection of an appropriate binder is essential. This begins with understanding the classification of available binders and their respective roles.

3.4.2. Classification and Selection of Binders

The selection of binders is influenced by several factors, including feedstock characteristics, end-use requirements, environmental regulations, cost, and local availability. Binders can be broadly categorized into five main types: (1) organic binders, (2) inorganic binders, (3) synthetic binders, (4) emerging green binders, and (5) compound binders. Each class offers advantages and limitations, which are explored below.

(1) Organic Binders

Organic binders are favored for their renewability, combustibility, and environmental compatibility. They generally produce briquettes with good mechanical strength, though they may degrade or fail at elevated temperatures [84,87]. Common organic binders include Lignosulphates, molasses, biomass-derived tar pitch, and natural polymers such as starch. Table 3 shows the commonly used binders along with their advantages and disadvantages.

Table 3. Classification of binders for fine coal and biomass briquetting.

Binder Type	Examples	Characteristics	Advantages	Limitations	References
Organic Binders	Molasses, starch, lignin, tar pitch, and gums	Renewable, combustible, and biodegradable	Clean-burning (e.g., starch); improves cohesion; renewable sources.	Poor thermal stability, high cost (e.g., PVA), and tar-based binders emit pollutants.	[88–90]
Inorganic Binders	Bentonite clay, cement, lime, and gypsum	Non-combustible and thermally stable	Readily available; improves mechanical strength and water resistance.	Increases mineral content, reduces the higher heating value, and unsuitable for domestic use.	[91–93]
Synthetic/Chemical	Bitumen, resins, sodium silicate, PVA, and synthetic polymers	Industrial-grade strength and chemically engineered	High performance in metallurgical settings.	Expensive, potential for toxic emissions, and not eco-friendly.	[94–96]
Emerging/Green	Microbial biopolymers, biochar binders, and waste binders	Biodegradable, carbon-neutral potential, and locally sourced	Eco-friendly; supports circular economy; often cost-effective.	Still under research, performance may vary, and scalability challenges.	[97–101]
Compound Binders	Molasses + lime; starch + clay; and biomass + bentonite	Combination of organic and inorganic or synthetic types	Balanced performance; tailored to specific applications.	Requires optimization, and may increase complexity or cost.	[102,103]

Among the binders shown in Table 3, the common organic binders are briefly discussed below:

- (a) Molasses: A sticky, carbon-rich organic binder derived as a byproduct of the sugar industry that enhances both the energy value and cohesive strength of briquettes [63]. Manyuchi et al. [20] showed that the addition of molasses in the co-densification of fine coal with sawdust increased the HHV and compressive strength of briquettes by 16% and 50%, respectively. This organic binder is extensively used in countries such as India, China, and SA, particularly in molasses–lime compound systems where its performance is complemented by the addition of lime to improve water resistance [104].

However, its hygroscopic nature may compromise briquette stability under humid conditions unless combined with water-resistant additives like lime [105,106].

- (b) Starch: The most widely used organic binder derived as a carbohydrate reserve from plants such as maize, cassava, and wheat [12,87]. This binder is clean-burning, making it suitable for high-quality briquettes used in indoor applications [36,87]. Chinyere et al. [90] observed an improved HHV from briquettes produced from sawdust when the amount of binder was increased from 30 mL per 100 g to 40 mL per 100 g, rising from 38.20 MJ/kg to 41.17 MJ/Kg. However, starch is relatively costly, which can limit its use in large-scale or low-budget operations. Its high hygroscopicity may also affect briquette stability in humid conditions, necessitating costly waterproofing additives.
- (c) Lignin: Naturally present in lignocellulosic biomass. It can act as a self-binder during high-pressure briquetting processes [107]. Mardiyati et al. [108] showed that binderless, all lignin briquettes from black liquor waste have a 99.7% drop-shatter index (DSI) and HHV equivalent to coal briquettes. In many systems, especially in Europe and North America, additional lignin is introduced to reinforce briquette durability. While effective, its utility is largely confined to woody biomass or feedstocks with high lignin content.
- (d) Vegetable oils: These include sunflower oil, palm oil, bio-oil, cooking oil, and castor oil. They are occasionally used as auxiliary binders or combustion enhancers [89]. In the co-densified briquetting of biomass, Zhang et al. [89] showed that the lubricating and combustible nature of both bio-oil and cooking oil can improve the ignition and burning behavior of briquettes. However, they are not primarily used for their binding capacity, as they often lack the cohesive strength necessary for durable briquettes [12,87]. Furthermore, their cost and variable quality are affected by factors like oxidation and purity, limiting their large-scale adoption in industrial briquetting [12,63,87,89].
- (e) Plant gums: These are polysaccharide-based organic compounds with natural adhesive properties, including guar gum, gum Arabic and acacia gum [109]. These are especially prevalent in artisanal and small-scale briquetting operations, including in rural or indigenous contexts [109]. Their biodegradability and non-toxic nature are advantageous, but their performance can be inconsistent due to MC sensitivity, microbial degradation, and relatively high costs. In line with this, Hassan et al. [110] observed that briquettes produced using gum Arabic as binder lowered the HHV of raw sawdust from 17.1 MJ/Kg to 15.7 MJ/kg.
- (f) Tar pitch: This organic binder is derived from coal tar distillation. It has historically been used in coal briquetting due to its strong adhesion, hydrophobicity, and ability to produce high-strength briquettes [88,111]. Zhong et al. [111] observed that using tar pitch to bind fine coal resulted in briquettes with improved DSI ($\times 50/1$ m) and a compressive strength of 6.43 MPa. However, tar pitch is not environmentally friendly, which restricts its use, as it releases toxic and carcinogenic compounds upon combustion [87,111].

Overall, organic binders are most suited to rural domestic use or SMME-scale operations where the ease of sourcing outweighs durability under harsh storage conditions.

(2) Inorganic Binders

Inorganic binders are typically mineral-based materials known for their thermal stability and strong binding capabilities. They are widely used where mechanical strength and water resistance are prioritized over HHV or combustion purity [12,41,87]. However, since these binders are non-combustible, they contribute to increased mineral content and a reduction in fuel efficiency.

Among the binders shown in Table 3, the common inorganic binders are briefly discussed below:

- (a) Bentonite Clay: Naturally occurring aluminosilicates are among the most common inorganic binders used in coal and biomass briquetting [87,91]. They are inexpensive, abundant, and enhance the structural strength and water resistance of briquettes [8,91,112]. These properties make them particularly useful in applications where briquettes are exposed to handling, moisture, or transport stress. However, their significant downside lies in their contribution to non-combustible residue. Bello et al. [91] recently analyzed the performance of clay as a binder and saw that the briquettes have poor flame propagation within the combustion chamber and delayed ignition time (7–10 min). These limitations make clay-based briquettes less ideal for residential combustion, where quick ignition and clean burn are preferred. As such, they are more suited to industrial or metallurgical briquettes than to those intended for residential or clean [8,112].
- (b) Lime ($\text{Ca}(\text{OH})_2$): Often used in its hydrated form ($\text{Ca}(\text{OH})_2$), lime acts as a binding and stabilizing agent, particularly in combination with organic binders such as molasses. It is frequently used in SA and Southeast Asia for improving the water resistance and long-term durability of bio-coal briquettes. Lime also helps neutralize acidic components and can slightly enhance combustion behavior. However, like other inorganic additives, lime increases mineral content and does not contribute to fuel value, requiring the careful optimization of dosage. Recently, Das et al. [92] compared various briquettes made of both organic (molasses, starch, pitch, and dextrin) and inorganic binders (lime and bentonite) to those made of fly ash bonded flue dust and observed that lime-based briquettes had the poorest compressive strength. Thus, blending it with other binders in a compound manner is a better option than using it solely.
- (c) Cement: This inorganic material is employed in briquetting processes where extreme mechanical strength is required, such as in metallurgical briquettes or construction-grade fuel blocks [14,15]. It has been shown to provide excellent compressive strength and resistance to handling damage. Ikelle [93] reported that coal briquettes formulated with cement exhibited exceptional durability but had significantly elevated ash levels (19.18–28.83%) and a long ignition time at 46 s. These trade-offs restrict cement's use primarily to non-combustion or industrial applications where fuel purity is not the primary concern. In addition, the carbon footprint associated with cement production presents a drawback from a sustainability standpoint.
- (d) Gypsum: It is occasionally added to briquette formulations, particularly in coal-based systems, for its sulfur-binding properties. It serves to reduce emissions such as sulfur dioxide during combustion, which is relevant for environmental compliance in industrial settings. However, like other inorganic binders, gypsum adds weight and ash to the final product and is not typically used in domestic fuel applications.

Overall, inorganic binders are better suited for industrial or metallurgical applications where strength and durability outweigh energy performance.

(3) Synthetic and Chemical Binders

Synthetic binders are often derived from petroleum or industrial chemical processes and utilized primarily in high-value or technically demanding briquetting applications such as steelmaking, metallurgy, or the production of composite fuels [12,87]. They are notable for their high performance in terms of mechanical strength, resistance to environmental degradation, and high-temperature stability. However, their cost, potential for harmful emissions, and lack of biodegradability restrict their broader adoption, especially in residential or sustainable energy systems [109].

Among the binders shown in Table 3, the common synthetic/chemical binders are briefly discussed below:

- (a) Bitumen and resin-based binders: These are widely used in industrial briquette applications where structural integrity must be maintained at high temperatures or under mechanical stress. These binders are particularly effective in forming coke or metallurgical briquettes. Bitumen, being hydrophobic, also imparts water resistance. However, its combustion releases polycyclic aromatic hydrocarbons (PAHs), making it unsuitable for household energy use. A study by Mousa et al. [94] demonstrated that incorporating 2% bitumen as a partial replacement for cement in blast furnace briquettes achieved sufficient mechanical strength and improved reduction rates, highlighting its potential in metallurgical applications.
- (b) Sodium silicate: This binder is used in niche applications. It provides excellent water resistance and binding strength, especially in composite or refractory materials [92]. Its chemical stability and fire resistance make it valuable in specialized industries [12,92]. A study on blast furnace dust briquettes conducted by Han et al. [95] found that a 2% addition of sodium silicate, combined with corn starch, enhanced both low-temperature and high-temperature strength, with compressive strength reaching up to 1796 N at 1250 °C. Nonetheless, sodium silicate is brittle when dry, can alter pH balance, and lacks environmental compatibility [87,92].
- (c) Polyvinyl alcohol (PVA): This is a water-soluble synthetic polymer sometimes included in the organic binder category due to its carbon-based composition and potential biodegradability under specific conditions [113,114]. It provides excellent adhesive strength and clean-burning properties, making it suitable for premium briquettes [115]. PVA was used as a binder by Henning et al. [113], producing briquettes with a 7% increase in compressive strength at 5% formulation. However, PVA is relatively expensive and thermally unstable above 200 °C, limiting its utility in high-temperature or large-scale industrial applications [12,115]. Moreover, it must be produced under controlled chemical processes, making local sourcing in resource-limited regions difficult.
- (d) Other synthetic polymers: These may include acrylic resins, epoxy compounds, and phenol–formaldehyde resins, which are occasionally used in advanced briquetting systems [87]. While these binders offer customizable properties, such as high heat resistance and moisture control, their use is limited to high-cost, high-precision applications due to environmental, safety, and cost concerns.

Overall, synthetic binders are limited to niche industrial applications; not viable for decentralized rural energy systems.

(4) Emerging and Green Binders

Amid increasing global interest in sustainability, significant research has turned toward the development of environmentally friendly and biodegradable binder alternatives. These green binders aim to minimize environmental impact, reduce reliance on fossil-derived materials, and improve compatibility with circular economy models.

Among the binders shown in Table 3, the emerging and green binders are briefly discussed below:

- (a) Microbial biopolymers: Polymers such as xanthan gum, exopolysaccharides (EPS's), and bacterial cellulose are produced through fermentation processes involving bacteria like *Bacillus* spp. or *Xanthomonas* spp. [97,98]. These binders offer excellent water-binding properties and biodegradable profiles, making them attractive for bio-coal briquetting [99,100,116]. In SA, institutions like the universities and local R&D institutions are actively exploring the production of these biopolymers using local microbial strains and agro-waste substrates. While promising, these binders are still undergoing pilot-scale testing and require further validation for commercial viability.

- (b) Biochar-based binders: Biochar represents another frontier in green binder technology. It is made from pyrolyzed biomass, producing a carbon-rich, structurally stable binder that can enhance the overall carbon content and HHV of briquettes [117]. Their compatibility with a wide range of feedstocks and their potential to serve as carbon-negative materials makes them highly attractive, particularly in regions focused on carbon trading or climate commitments [87,117,118].
- (c) Waste-derived binders: These include binders made from paper sludge, sawdust waste, distillery effluents, or other industrial byproducts [87,119]. They are being evaluated for their binding potential in countries like India, Brazil, Kenya, and Indonesia [87,102,119]. These binders support waste valorization while offering cost-effective alternatives to synthetic or imported materials. Their performance varies widely depending on the source material, processing, and formulation, and standardization remains a challenge.

Overall, green binders are promising for pilot-scale trials and municipal or industrial partnerships where infrastructure and feedstock consistency can be ensured.

(5) Compound binders

Compound binders are two or more binders that come with some added advantage over the traditional use of single binders. The combined strengths of each type of binder come into effect to improve the overall properties of the briquettes. Inorganic binders like bentonite can be used to improve the mechanical properties of the briquettes when mixed with organic binders [120]. Various combinations have been studied, including molasses–lime blend [104], starch–clay blend [103], and various organic biomass binder blends with bentonite [120]. These binders are best suited for customized local formulations, especially in regions with access to agro-waste and small-scale processing infrastructure.

Among the available options, molasses and microbial biopolymers emerge as the most promising binders for widespread application in SA. Molasses, a byproduct of the country's well-established sugar industry, is readily available, especially in sugarcane-producing regions such as KwaZulu-Natal and Mpumalanga, which also host major coal mining operations. Its sticky, carbon-rich nature makes it highly compatible with both fine coal and biomass, enhancing both energy content and briquette cohesion. Additionally, molasses is biodegradable, relatively inexpensive, and aligned with circular economy goals. On the other hand, microbial biopolymers such as xanthan gum and EPS produced by *Bacillus* spp. or *Xanthomonas* spp. offer biodegradable, non-toxic binding capacity with strong mechanical performance [97,98]. These biopolymers can be locally cultivated using agro-industrial waste streams such as molasses itself, distillery waste, or agricultural residues, supporting low-cost, decentralized production models. South Africa's active research infrastructure, particularly institutions like the CSIR, could provide support for piloting and scaling biobased production. The combined use of molasses and microbial biopolymers as a compound binder system can offer several synergistic advantages:

- Improved mechanical strength and moisture resistance of briquettes, particularly under variable storage and transport conditions;
- Enhanced combustion performance with reduced toxic emissions, supporting cleaner energy transition goals;
- Reduced reliance on expensive or imported synthetic binders;
- Local value addition through the utilization of byproducts and biotechnology, stimulating rural and industrial economies.

In the SA context, where diverse feedstocks, ranging from coal fines to agricultural waste, coexist with industrial and research capabilities, the strategic development of molasses–biopolymer compound binders offers a technically viable, economically accessi-

ble, and environmentally responsible solution for scalable bio-coal briquetting. Pilot studies are needed to validate this combination's effect on improving briquette HHV, structural integrity, and environmental sustainability.

3.4.3. Binderless Briquetting

In contrast to the binders discussed above, binderless briquetting is a densification process that relies solely on the natural binding components present in the feedstock [57]. These primarily include lignin, MC, and thermal-softened cellulose without the addition of external binders [57,121,122]. This method is particularly suitable for feedstocks with high lignocellulosic content, such as woody biomass and certain types of agricultural residues [56,57,108].

Under high pressure (>100 MPa) and elevated temperatures (ranging from 100 to 200 °C), lignin within biomass becomes thermoplastically active and acts as a natural binder. This phenomenon, known as thermoplasticity, allows particles to fuse, producing structurally cohesive briquettes [57,108].

In comparison to binder-based briquetting, binderless briquetting offers several advantages:

- Cleaner combustion: No added binders means no external emissions from binder combustion, improving air quality and reducing mineral content [56,57].
- Simplified supply chain: Eliminates the need to procure, store, and handle binders, lowering production complexity and operational costs.
- Sustainability: The process aligns with circular economy principles by avoiding non-renewable or environmentally harmful additives.

However, binderless briquetting also has significant technical constraints:

- Feedstock specificity: Only feedstocks with sufficient lignin content (e.g., wood, straw, and bagasse) are viable; fine coal or low-lignin biomass requires binders [57].
- Higher energy requirements: Elevated pressures and temperatures increase the energy input and mechanical wear on equipment [56,57].
- MC sensitivity: Binderless briquettes can suffer from poor water resistance and degrade under humid conditions unless post-treated [21,56].

In the SA context, binderless briquetting may be well-suited to regions with abundant woody biomass or sugarcane bagasse (e.g., Mpumalanga and KwaZulu-Natal), but coal-dominated feedstocks and high ash biomass residues prevalent in SA often require binder augmentation to meet mechanical and combustion standards. While binder selection plays a central role in determining briquette quality, optimal performance also depends heavily on key manufacturing parameters such as pressure, temperature, and particle size. These parameters are explored in the next section.

3.5. Manufacturing Parameters and Process Optimization

The quality, strength, and combustion efficiency of fine coal briquettes are significantly influenced by key manufacturing parameters such as pressure, temperature, MC, particle size, and residence time [87]. Each of these variables governs the degree of densification, inter-particle bonding, and ultimately the physical and thermal properties of the final product [39,85]. Optimization of these parameters is critical for achieving consistent briquette performance using heterogeneous feedstocks like fine coal and biomass. This section discusses the role of these process variables and introduces optimal material parameters that directly affect briquette efficiency, particularly in co-densification systems.

3.5.1. Key Manufacturing Variables

The briquetting process is governed by several interdependent manufacturing variables that influence the physical integrity, energy content, and combustion behavior of the

final briquettes. Optimizing these parameters is particularly important, where feedstock heterogeneity and infrastructure limitations require process adaptability. The key variables (a) pressure, (b) temperature, (c) moisture content, (d) particle size and (e) mixing, and (f) residence time are summarized in Table 4 and discussed below.

Table 4. Key manufacturing variables in fine coal briquetting.

Variable	Optimal Range	Function/Effect	References
Pressure	80–150 MPa	Facilitates particle bonding through plastic deformation, friction, and van der Waals forces.	[51,87]
Temperature	Ambient to 200 °C	Enhances binder reactivity and softens biomass lignin in binderless briquetting.	[89,106,123]
Moisture Content	8–15 wt%	Acts as binder activator and lubricant; affects compaction and drying behavior.	[14,123,124]
Particle Size	≤3 mm (ideal: 0.5–2 mm)	Impacts packing density and inter-particle contact area.	[125,126]
Mixing Time	Mixing: 5–30 min	Ensures uniform binder dispersion and sufficient bond formation under pressure.	[79,118]
Residence Time	1–5 s (press dwell time)	Allows stress relaxation and bond formation during compression.	[39,49,51]

- (a) **Pressure:** Compaction pressure is one of the most critical factors affecting briquette strength and durability. High-pressure systems (>100 MPa), such as piston and roller presses, facilitate strong inter-particle bonding through mechanisms like plastic deformation, van der Waals forces, and mechanical interlocking [51,87]. Optimal pressure levels vary depending on feedstock composition and binder type, with a common effective range of 80–150 MPa for coal–biomass blends [51]. However, excessive pressure can lead to equipment wear and high energy consumption. In SA, where high-rank coal fines dominate, pressure must be carefully optimized to overcome coal’s natural rigidity without causing excessive equipment wear or energy consumption.
- (b) **Temperature:** Although the briquetting of coal fines is commonly conducted at ambient temperatures, moderate thermal input (100–200 °C) can significantly improve binding. This was confirmed by Nurek et al. [123], who produced briquettes with higher durability at 72 °C compared to an ambient temperature of 22 °C. In binderless systems, this heat softens lignin in biomass, enhancing cohesion [57]. For binder-based compound systems such as molasses–lime blends widely used in SA, elevated temperatures accelerate chemical curing, improving briquette integrity [92]. However, excessive heat may lead to premature MC loss and material degradation.
- (c) **Moisture Content:** Moisture plays a dual role as both a lubricant during compaction and an activator for certain binders [18,127]. Many researchers have identified that the optimal MC range typically lies between 7 and 15 wt% depending on binder type and feedstock characteristics [14,123,124]. Insufficient moisture reduces compressibility and cohesion, while excess moisture promotes steam formation, cracking, and strength loss during drying [123,124].
- (d) **Particle Size:** Feedstock particle size has been found to directly impact packing density and binding surface area [125,126]. These in turn influence both compressive strength and energy density of the briquettes [126]. Particles <3 mm have been observed to

enhance compaction, but excessive fines (<0.2 mm) can impair permeability and slow drying, thereby reducing production efficiency and increasing energy input during curing [86,125,128]. A well-graded particle size distribution, often achieved via crushing and screening, ensures the homogeneity and structural stability of the briquettes. A well-graded distribution, typically 0.5–2 mm is optimal. Mani et al. [129] showed that optimizing particle size improves briquette density, strength, and combustion. Haidai et al. [130] emphasized the need to evaluate granulometric composition in composite fuels to control ash behavior and compaction. This study noted that variations in particle size distribution significantly affect compaction, higher heating value, and ash behavior. Additionally, Nati et al. [131] highlighted how screen selection and blade wear affect size uniformity and energy efficiency. In the SA context, standardizing crushing and screening, coupled with PSD–binder compatibility trials, could enhance briquette quality and process efficiency.

- (e) **Mixing time:** Uniform mixing of binders and feedstocks is essential for producing consistent and high-quality briquettes. Adequate mixing promotes the homogeneous distribution of the binder across all particles, enhancing inter-particle contact and matrix cohesion [83]. Mixing times typically range from 5 to 30 min depending on the binder type, moisture level, and feedstock composition [86,87].
- (f) **Residence time:** Residence time refers to the duration that the material remains under compression within the briquetting chamber. Sufficient residence time is crucial to allow stress relaxation and promote the physical and chemical bond formation between particles [39,83]. This becomes particularly important when using temperature or MC-sensitive binders such as starch, molasses, or microbial biopolymers, which require a short but controlled period to set effectively under pressure.

In SA, optimizing these parameters requires careful consideration of the local coal profile, which typically features high mineral content and variable levels of VM and sulfur [21,56,132]. Regional pilot studies conducted by organizations such as Coaltech© and the University of Pretoria have demonstrated that compaction conditions must be tailored to feedstock type [9,21,25]. For example, in KwaZulu-Natal and Mpumalanga, where bagasse and sawdust are commonly blended with fine coal, adjustments in MC and extended dwell times are necessary due to the fibrous, lignin-rich nature of the biomass.

3.5.2. Optimal Quality Parameters

Beyond process conditions, the intrinsic properties of the briquette feedstock and final product significantly influence combustion behavior, handling characteristics, and energy efficiency. The following parameters are critical to assess and optimize:

- (a) **Higher Heating Value:** A key metric for energy output, the target HHV for bio-coal briquettes ranges between 18 and 26 MJ/kg [133]. Blending high HHV fine coal (20–25 MJ/kg) with lower HHV biomass (<15 MJ/kg) must be balanced to achieve a competitive fuel value.
- (b) **Moisture Content:** Target MC in final briquettes should not exceed >10% to ensure good ignition and minimize transport cost [87,134]. Excessive moisture lowers HHV and combustion efficiency [87].
- (c) **Volatile Matter:** Higher VM (20–35%) enhances the ease of ignition and flame propagation [135]. Biomass typically increases VM in the blend, which compensates for the low reactivity of high-rank coal.
- (d) **Fixed Carbon (FC):** Indicates the solid carbon available for sustained combustion. Optimal FC (>50%) ensures steady heat release during industrial or domestic use [136]. Biomass has lower FC, so the coal content needs to be sufficient to maintain heat value.

- (e) Bulk Density: Higher bulk density (0.9–1.2 g/cm³) improves energy density, transportation economics, and storage efficiency. This is especially important for off-grid or rural distribution in SA.
- (f) Burning Rate and Combustion Time: These parameters are influenced by both VM and structural integrity [95,136]. Ideal briquettes should burn uniformly with minimal sparking or fragmentation, suitable for both household stoves and industrial furnaces.
- (g) Mineral content and Composition: Lower mineral content (<15%) is preferred to reduce residue disposal and enhance thermal efficiency [91,137]. Inorganic binders like clay or lime raise ash levels, and hence should be used cautiously. In SA, the coal is often ash-rich, necessitating careful blending and binder selection to stay within optimal limits [76].

Optimizing the manufacturing parameters, such as pressure, temperature, moisture, particle size, mixing, and residence time, is essential to achieve briquettes with high mechanical strength, consistent combustion properties, and durability under storage and transport conditions. These variables must be tailored to the specific characteristics of SA fine coal and locally available biomass feedstocks, with due consideration to binder type and end-use application. Pilot-scale demonstrations in regions like Mpumalanga and KwaZulu-Natal underscore the importance of site-specific adjustments, especially given the variability in coal mineral content, VM, and sulfur levels. Once briquettes are produced under optimized conditions, it becomes essential to assess their physical and thermal performance to ensure suitability for end-use. The subsequent section outlines the key testing methods and relevant standardization frameworks necessary to guarantee quality and regulatory compliance.

3.6. Testing and Standardization

3.6.1. Performance Testing of Coal Briquettes

The evaluation of briquette quality is critical for ensuring performance consistency, user safety, and regulatory compliance. This section outlines the key physical (durability and strength) and thermal testing protocols used to assess briquette strength, durability, and combustion behavior (Figure 4). It also explores existing standards such as those from the South African Bureau of Standards (SABS), International Organization for Standardization (ISO), and ASTM International, identifying the current gaps and opportunities for developing context-specific testing frameworks to support industrial adoption and rural deployment of briquetting in SA.

Physical tests evaluate the mechanical integrity and handling resilience of briquettes during storage, transport, and end-use. These tests are essential to ensure briquettes can withstand physical stresses without excessive fragmentation, which could reduce combustion efficiency and increase fines loss. Thermal testing evaluates the energy performance and combustion characteristics of briquettes, which are vital for comparing them to traditional coal and for meeting user expectations in both domestic and industrial applications. Some of the main quality tests are detailed below:

- (a) Drop Resistance Index: Drop strength tests simulate accidental handling shocks. The test involves dropping briquettes from a standard height (typically 2 m) onto a hard surface multiple times and measuring the percentage of mass retained. ASTM D-3038 for DSI of coke provides procedures for solid biofuels, while local protocols in SA use simplified adaptations for fuel evaluations [138]. However, the tests are rarely standardized across labs, reducing data comparability. SABS should define uniform drop protocols for rural settings.
- (b) Abrasion Resistance: This test determines the friability of briquettes under abrasive conditions (e.g., during transit). It is especially relevant for dusty or loosely bound

formulations. ISO 17831-1 standards are often used for wood pellets and biomass briquettes and can be adapted to fine coal applications [115,139]. South African labs such as SABS have begun to incorporate these methods in bio-coal quality assurance protocols.

- (c) **Water resistance:** This test indicates the briquette's durability in humid or wet conditions. This is particularly important due to possible open-air storage and seasonal rainfall. Water-resistant briquettes retain their shape and strength after short-term water exposure. Testing typically involves immersing briquettes in water for a set time (e.g., 30 min–1 h) and evaluating swelling, disintegration, or strength loss [140]. According to Richards [140], optimum resistance is stability beyond 1 h, which is globally accepted. Hydrophobic binders (e.g., pitch and wax emulsions) and additives like lime improve water resistance. However, SA lacks a formal moisture durability index for bio-briquettes, despite molasses and starch-based binders being hygroscopic. A local 'wet integrity test' could guide binder formulation optimization.
- (d) **Compressive Strength:** This test measures the maximum load a briquette can withstand before failure. It is a key indicator of structural integrity, especially during stacking or bulk handling. According to ISO 4700 (originally developed for metallurgical pellets but commonly adapted for solid fuels), a compressive strength above 1.0–1.5 MPa is generally considered acceptable for bio-coal briquettes [141]. South African studies often use similar thresholds when testing molasses- or starch-bound briquettes.
- (e) **Shear Strength:** This test evaluates the internal cohesion and resistance to sliding between particles in a briquette under lateral stress, complementing compressive strength assessments [142]. It is particularly relevant for briquettes made with low-viscosity or bio-based binders (e.g., molasses and starch), which may exhibit good compressive integrity but shear failure during handling or bulk transport. Shear strength is commonly measured using a direct shear apparatus based on ASTM D3080, originally developed for soil testing but increasingly adapted for assessing low-cohesion solid fuels [142]. Although no formal threshold exists for briquettes, preliminary studies suggest a minimum shear resistance of 0.5–1.0 MPa to ensure stability under stacking and loading stresses. Integrating shear strength testing can guide binder and feedstock optimization, particularly in humid or rural settings where briquettes face non-uniform stresses during storage and handling.
- (f) **Higher Heating Value (HHV):** The HHV measures the energy released during combustion and is the most important indicator of fuel efficiency. Standard methods include ASTM D5865 and ISO 1928, which use bomb calorimetry [143]. In SA, labs affiliated with universities (e.g., Wits and Stellenbosch) and organizations like SABS apply these methods for both raw coal and bio-coal blends. Target HHV for bio-coal briquettes is 18–26 MJ/kg depending on the blending ratio. However, most tests do not isolate combustion synergy between biomass and coal, which may under- or overestimate real-world efficiency.
- (g) **Ignition Time and Burn Rate:** These tests determine how quickly briquettes ignite and how long they sustain combustion. Biomass-rich briquettes tend to ignite faster due to higher VM content [77,80,87]. Standard protocols for these properties are less uniform but often draw from ISO 18123 (for proximate analysis) and ASTM E870-82 (2019) (wood fuel testing) [144]. Local tests in SA often involve field-based stove trials or controlled combustion chambers to assess real-world performance. Field stove trials or ceramic pot stove (CPS) setups should be standardized for rural contexts to measure practical performance [63,87].

- (h) Mineral content: High mineral content reduces HHV and complicates ash disposal. Measurement follows ASTM D1102 and locally for coal–biomass mixtures, SANS 5924 may also be adapted [145]. South African coal typically contains 25–45% ash, necessitating optimized blends with low-ash biomass and careful binder selection [56].
- (i) Emissions Testing: Although not nationally mandated in SA, emission testing (e.g., CO, SO₂, NO_x, and particulate matter) is gaining relevance for regulatory compliance and environmental health. Internationally, ISO 14064 provides guidelines for measurement setups for greenhouse gases [146].

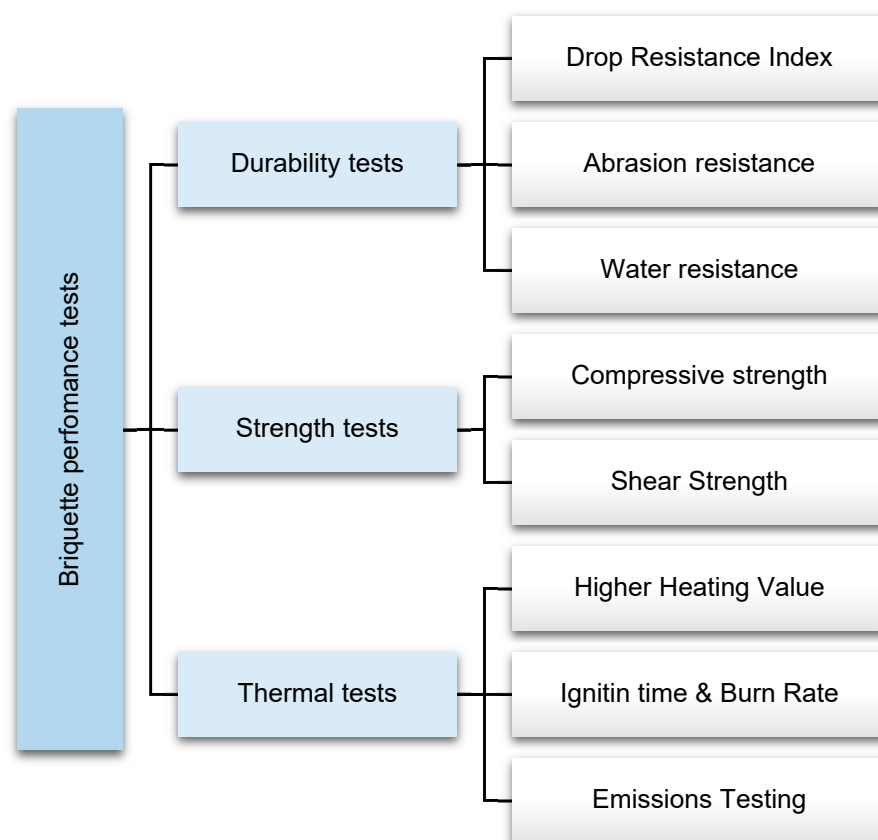


Figure 4. Overview of key briquette performance tests across routine, durability, strength, and thermal evaluation stages.

While current testing protocols from SABS, ASTM, and ISO provide useful benchmarks for assessing briquette quality, such as moisture content, density, compressive strength, and higher heating value, these standards were primarily developed for either conventional coal or biomass fuels. As such, they may not fully account for the unique physico-chemical behavior of hybrid bio-coal briquettes, particularly those incorporating bio-based binders. For instance, the existing durability indices may not reflect the mechanical stability of briquettes with organic binders under humid storage conditions, and standard heating value protocols often overlook synergistic effects between coal and biomass during co-combustion [147]. Although bio-based briquettes are ultimately evaluated for performance alongside those made with conventional binders, there is a critical gap in testing protocols that specifically address the properties and degradation mechanisms of bio-based formulations. This lack of tailored standards may unfairly disadvantage bio-binder technologies despite their sustainability benefits, hindering their adoption at scale.

To improve standardization, targeted adaptations could include the following:

- The development of hybrid testing protocols that evaluate co-firing emissions, volatile matter interactions, and ash fusion characteristics specific to coal–biomass blends;
- The introduction of dedicated water resistance and hygroscopicity indices, particularly for briquettes using bio-binders, which are prone to moisture absorption and mechanical degradation;
- The inclusion of field-appropriate drop strength tests and weathering resistance assessments for SMME and rural production settings;
- The calibration of minimum performance thresholds by SABS (e.g., acceptable density, HHV, and durability ranges) based on real-world end-use conditions in informal or decentralized markets.

Establishing these adapted standards in collaboration with institutions such as SABS and academic research hubs would not only enhance quality assurance but also ensure that bio-based innovations are assessed on a level playing field, thereby enabling the broader commercialization and credibility of bio-coal briquettes.

3.6.2. Standardization Frameworks for South Africa

Standardization ensures that briquettes meet performance, safety, and environmental criteria suitable for domestic and industrial applications. While SA currently lacks a comprehensive national briquette standard, several international and regional frameworks provide essential benchmarks for assessing product quality.

In SA, the SABS provides limited direct standards for densified solid fuels. However, SANS 17246 is often used as a proxy for grading and evaluating coal-based briquettes [148]. Institutions such as CSIR, Coaltech©, and local universities involved in coal research must contribute to developing local or project-based quality benchmarks, particularly for bio-coal applications, to meet the growing demands of the industry in the country. There remains a pressing need for formal briquette-specific standards tailored to local feedstocks and combustion technologies. To harmonize with global trade and emission norms, SA could adapt international standards while factoring in local variations. Developing national briquette standards under SABS would support product certification, consumer confidence, and cleaner fuel policies. Furthermore, it is recommended that SABS and academic consortia develop a simplified testing toolkit for rural or decentralized settings, including manual drop–shatter tests, basic calorimetry using portable bomb calorimeters, and low-cost water resistance assays using standardized immersion protocols.

Beyond the technical feasibility, the true value of bio-coal briquetting lies in its potential integration into SA's evolving energy policies. The next section examines how briquetting aligns with national priorities under the Just Energy Transition framework.

3.7. Integrating Bio-Coal Briquetting into South Africa's Just Energy Transition Framework

South Africa's energy landscape is undergoing a significant transformation under the Just Energy Transition (JET) framework, which aims to shift from fossil fuel (especially coal) dependency to a low-carbon economy while safeguarding jobs and promoting social equity [149]. Bio-coal briquetting offers a compelling entry point into this transition, particularly for rural and marginalized communities that are often left behind by centralized energy reforms.

Fine coal waste, abundant in mining provinces like Mpumalanga and Limpopo, represents a localized feedstock that can be valorized through low-cost briquetting operations. When combined with biomass residues (e.g., sugarcane bagasse, macadamia shells, or corn cobs) and regionally sourced binders (e.g., molasses or starch), briquette production can generate jobs across the value chain, from biomass collection and binder processing to

briquette manufacturing and distribution. Further, it enables knowledge transfer for rural communities to repurpose waste such as fine coal.

This decentralized model aligns with DFFE's Circular Economy Action Plan and the objectives of the Presidential Climate Commission, which emphasize inclusivity and community-driven clean energy projects [60]. Small-scale briquetting enterprises could also reduce pressure on forests (by replacing firewood), improve respiratory health by reducing indoor air pollution, and unlock economic activity in underdeveloped regions.

Moreover, the integration of briquetting into coal mine closure plans could enable affected communities to transition toward sustainable livelihoods. By valorizing existing waste streams and engaging informal labor, briquetting complements the JET principles of equity, access, and local empowerment.

To address key implementation barriers and fully realize this potential, the following strategic actions are recommended:

- Invest in local R&D focused on low-cost, biodegradable binders, particularly those derived from agricultural or agro-industrial waste such as molasses and starch, and explore the use of microbial exopolymers.
- Promote decentralized briquetting enterprises in coal-rich but energy-poor provinces (e.g., Limpopo and Mpumalanga) to empower SMMEs, support rural livelihoods, and enhance energy security.
- Incentivize briquetting initiatives through inclusion in national waste-to-energy schemes, mine closure plans, and the broader Just Energy Transition framework.
- Collaborate with standards bodies (e.g., SABS) to develop performance-based testing protocols specific to bio-coal briquettes, including water resistance, combustion behavior, and long-term durability.
- Strengthen public–private partnerships to improve market access, scale up infrastructure, and align briquetting initiatives with carbon offset programs and green procurement mandates.

Having considered policy integration and strategic implementation, it is equally important to understand the practical applications of briquetted products across different sectors. This is elaborated in the following section [60,149].

4. End-Use Applications

Coal briquetting serves as a practical solution to the global challenge of fine coal utilization, transforming dusty, combustible waste into dense, manageable fuel or feedstock. Briquettes offer improved handling, reduced dust emissions, and more efficient combustion. This is particularly valuable in SA, which produces over >10 million tonnes of fine coal annually, much of which is underutilized.

Globally, coal briquettes are used in domestic heating, small boilers, metallurgical processes (e.g., COREX/FINEX), and coke ovens to improve productivity and reduce costs [39,89,150]. In SA, historical applications included Sasol's experiments with binderless briquetting for gasification and Iscor's pitch-bound briquettes for blast furnace coke [37]. While these were discontinued due to cost factors, the current efforts increasingly align with circular economy goals, valorizing coal waste through briquetting and reducing environmental impact. Table 5 below summarizes key applications both globally and in the SA context. Despite economic challenges, especially binder costs, coal briquetting remains a promising strategy to convert CMW into useful energy products.

Table 5. Applications of coal briquettes in global and South African contexts.

Sector	Source Material	Agglomeration Technique	Application/End Product	Key Benefit	Region	References
Residential and Small Industry	Coal fines and lignite	Briquetting	Domestic fuel for stoves and boilers	Improved combustion and easier handling	Global/SA	[17]
Metallurgy (Steel)	Fine coal and pitch binder	Partial briquetting	Coke oven feedstock (e.g., Iscor)	Enhanced coke strength and reduced dust loss	SA	[80,122,132]
Energy Conversion	Fine coal (binderless)	High-pressure briquetting	Gasifier feedstock (e.g., Sasol)	Feedstock densification and binder cost reduction	SA	[14,21,56,57]
Industrial Processes	Coal fines and biomass	Briquetting	Co-firing fuel in boilers and furnaces	Renewable blending and reduced emissions	Global/SA	[87,89,127]
Circular Economy	Coal waste and rejects	Agglomeration and briquetting	Fuel or additives for other industries	Waste valorization and reduced disposal cost	SA	[150]

5. Opportunities and Challenges

While bio-coal briquetting holds great promise, translating this potential into real-world impact requires a critical understanding of both the opportunities it presents and the practical challenges it faces. This section discusses key barriers and enabling factors that influence implementation.

5.1. Overview

The world is seeking alternative energy resources because of the depletion of fossil fuel reservoirs like crude oil, coal, and natural gas in the next few decades. Worldwide coal mining and processing operations inevitably result in tonnes of accumulation of fine coal (<1 mm) and ultrafine coal (i.e., <100 µm), which commonly end up in slime dams and landfills, which is environmentally unsustainable. At research institutes, efforts focus on sustainable product and process development, and one such initiative is the efficient usage of waste energy resources such as fine coal. In this aspect, unutilized coal waste and sustainable biomass are considered major energy contributors to convert biomass-blended fine coal into high-quality solid briquettes. Furthermore, the beneficiation of fine coals is the main purpose of valorization projects, whereby the focus is on integrating different bio-based binders for briquette processing technologies.

Research around the world is shifting focus to the incorporation of bio-based binders in briquette production, which is advantageous as biomass feedstocks usually end up as waste will be redirected, and further, it is aligned with local and global initiatives focusing on sustainable production and circular economy strategies. In addition, it is envisaged that in this project, this new coal briquette could yield and improve combustion characteristics compared to traditional coal briquettes and reduce mineral content. The overall benefit is twofold: environmental sustainability and cost effectiveness. These processes make briquettes environmentally ‘cleaner’ and also enhance human health by reducing the exposure to harmful pollutants/chemicals. In addition, the integration of eco-friendly raw feedstocks enables participation in the global green energy market, which is projected to reach over 60 billion USD by 2034 [151]. In SA, these briquettes also offer SMMEs and rural households a cleaner, cost-effective alternative to electricity amid a persistent 4000–6000 MW power deficit [2]. While these developments signal progress, widespread

adoption remains constrained by several logistical, economic, and market-related barriers, particularly in rural or under-resourced regions.

5.2. Practical Implementation Challenges and Opportunities

Despite its technical feasibility, the real-world adoption of bio-coal briquetting in SA faces several barriers. However, several initiatives have been implemented by the government to incorporate the use of locally manufactured biobased binders and involve research grants (CoalTech/Sasol/ESKOM) to simultaneously achieve ‘green’ biobased coal and other value-added products [152]. Key among these is feedstock logistics, as biomass residues are often seasonal, scattered, or located far from coal mining zones. This raises transportation and storage costs, undermining cost-efficiency for rural producers. In addition, the high cost and inconsistent supply of binders such as molasses, gum Arabic, and water-resistant binders (i.e., polymers) limit scale-up, especially where agricultural supply chains are underdeveloped.

Scalability is also constrained by the lack of access to briquetting equipment and reliable electricity in off-grid areas. While manual briquetting methods offer a low-cost entry point, they often yield lower-quality briquettes, hindering market competitiveness. Market development remains weak due to limited consumer awareness, the absence of product certification, and competition from subsidized alternatives like coal or firewood.

Despite the growing urgency for cleaner solid fuel alternatives, SA’s domestic bio-coal sector remains underdeveloped. For example, SASOL, one of the country’s largest coal users in the petrochemical industry, has recently shown interest in pivoting toward briquettes. However, the company currently relies on imported products from U.S.-based EESTech© due to the absence of suitable local suppliers. While a few SA companies such as E&C Charcoal©, SHISA Eco Briquettes©, Bosveld Charcoal©, and Eco-Coal© are active in biomass-based briquetting, none have yet developed products compatible with the technical and volumetric requirements of large-scale gasification operations like those at SASOL.

To address these limitations, the establishment of decentralized production hubs near biomass and coal sources should be prioritized. These hubs could be supported through public–private partnerships or integrated into municipal waste-to-energy programs. Strategic collaboration between institutions such as CSIR, Coaltech, SASOL, ESKOM, and research-intensive universities is critical for co-developing robust briquetting technologies that serve both industrial-scale operations and household energy needs. Supporting both the existing and emerging SMEs in the bio-coal sector is essential to unlocking SA’s circular energy potential through a coordinated innovation axis that links SA based industries, and local universities, where targeted support can be provided in the form of pilot funding, technology transfer, technical incubation, and quality assurance. This collaborative framework can accelerate the development of SME-led briquetting enterprises capable of meeting both industrial-grade specifications and rural household needs while simultaneously fostering local job creation and resilient energy solutions.

Capacity building, particularly among women and youth in rural areas, is critical. Also, to overcome rural equipment barriers, it is recommended that SA’s SETA and TVET college networks be engaged in the manufacturing and servicing of manual briquetting presses under public–private innovation grants. Lastly, policy mechanisms such as green procurement mandates or inclusion of bio-coal in carbon offset programs for every coal mine could catalyze adoption and unlock circular economy synergies.

6. Conclusions and Recommendations

6.1. Conclusions

Bio-coal briquetting presents a technically feasible and environmentally aligned strategy for valorizing South Africa's vast reserves of fine coal waste, especially when co-densified with locally available biomass residues. This review highlights that co-briquetting not only improves the fuel properties of low-grade coal (e.g., higher heating value, lower ash content, improved structural integrity), but also supports decentralized energy production, reduces environmental hazards associated with tailing dams, and creates inclusive economic opportunities in underdeveloped regions. In conclusion, bio-coal briquetting offers a transitional pathway toward a cleaner, more inclusive energy system in South Africa, bridging environmental management with rural industrialization and energy security.

Key findings demonstrate the following:

1. SA possesses diverse biomass resources including macadamia shells, sugarcane bagasse, and corn cobs that are suitable for blending with fine coal.
2. Organic binders like molasses and starch, along with emerging microbial biopolymers, are particularly promising for low-emission, high-performance briquettes.
3. Optimal briquetting parameters (pressure, particle size, and MC) directly influence briquette quality and need to be localized based on coal type and biomass blend.
4. Integration into the JET, mine closure plans, and circular economy policies enhances socio-economic relevance.

6.2. Recommendations

To support the large-scale adoption and long-term success of bio-coal briquetting in SA, targeted policy and industry interventions are required. These should address gaps in technology commercialization, standardization, enterprise development, and market integration, particularly in historically marginalized regions or areas that are coal-rich but energy-poor. The following recommendations are proposed:

Policy and industry recommendations include the following:

1. Investing in local R&D for cost-effective biodegradable binders derived from agro-waste;
2. Establishing decentralized briquetting enterprises in energy-poor, coal-rich provinces to support SMMEs and job creation;
3. Local research institutes must collaborate with SABS to develop standardized testing protocols tailored to hybrid briquettes;
4. Including bio-coal briquetting in national waste-to-energy schemes and carbon offset mechanisms;
5. Strengthening public-private partnerships to scale infrastructure and stimulate rural energy markets.

In parallel, supporting, advancing bio-coal briquetting technologies will require sustained research to validate technical performance, improve economic feasibility, and ensure long-term environmental and social sustainability. The following areas are recommended for future investigation:

Future research should focus on the following:

1. Pilot-scale validation of compound binder systems (e.g., molasses + microbial EPS);
2. Long-term field performance of briquettes under varied storage, weather, and combustion conditions;
3. Life-cycle and techno-economic analyses to assess cost-effectiveness and climate impact;

A robust future research agenda will be essential for optimizing feedstock blends, enhancing briquette durability under real-world conditions, and enabling local enterprises

to scale with confidence. These studies will also help align briquetting innovations with national energy, environmental, and socio-economic development goals.

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References

1. International Energy Agency. *Coal 2023—Analysis and Forecast to 2026*; International Energy Agency: Paris, France, 2023.
2. ESKOM. *Generation Communication: CO 0007—Revision 16 COAL In SOUTH AFRICA*; ESKOM: Sandton, South Africa, 2021.
3. International Energy Agency. *Electricity 2024—Analysis and Forecast to 2026*; International Energy Agency: Paris, France, 2024.
4. Statistics South Africa. *Statistics South Africa General Household Survey*; Statistics South Africa: Pretoria, South Africa, 2021.
5. Smit, S.; Musango, J.K. Exploring the Connections between Green Economy and Informal Economy in South Africa. *S. Afr. J. Sci.* **2015**, *111*, 10. [[CrossRef](#)] [[PubMed](#)]
6. Du Venage, G. South Africa Comes to Standstill with Eskom's Load Shedding. 2020. Available online: <http://www.e-mj.com/news/this-month-in-coal/south-africa-comes-to-standstill-with-eskoms-load-shedding/> (accessed on 3 May 2025).
7. Grant-Stuart, D.J. *Your Tailings Dam*; The South African National Committee on Large Dams: Pretoria, South Africa, 2020.
8. Rebelo, W.B.; Zaccaron, A.; Saviatto, E.; Olivo, E.F.; Acordi, J.; Raupp-Pereira, F.; Ribeiro, M.J. Valorization of the Residual Fraction of Coal Tailings: A Mineral Circularity Strategy for the Clay Ceramic Industry in the Carboniferous Region of Santa Catarina, Southern Brazil. *Materials* **2024**, *17*, 2131. [[CrossRef](#)] [[PubMed](#)]
9. Amaral, F.J.R.d.; Gcayiya, M.; Kotsiopoulos, A.; Broadhurst, J.L.; Power, D.; Harrison, S.T.L. Valorization of South African Coal Wastes through Dense Medium Separation. *Minerals* **2022**, *12*, 1519. [[CrossRef](#)]
10. Cui, C.Q.; Wang, B.; Zhao, Y.X.; Xue, L.M. Waste Mine to Emerging Wealth: Innovative Solutions for Abandoned Underground Coal Mine Reutilization on a Waste Management Level. *J. Clean. Prod.* **2020**, *252*, 119748. [[CrossRef](#)]
11. Akinbami, O.M.; Oke, S.R.; Bodunrin, M.O. The State of Renewable Energy Development in South Africa: An Overview. *Alex. Eng. J.* **2021**, *60*, 5077–5093. [[CrossRef](#)]
12. Zhang, G.; Sun, Y.; Xu, Y. Review of Briquette Binders and Briquetting Mechanism. *Renew. Sustain. Energy Rev.* **2018**, *82*, 477–487. [[CrossRef](#)]
13. Rubio, B.; Izquierdo, M.T.; Segura, E. Effect of Binder Addition on the Mechanical and Physicochemical Properties of Low Rank Coal Char Briquettes. *Carbon N. Y.* **1999**, *37*, 1833–1841. [[CrossRef](#)]
14. Venter, P.; Naude, N. Evaluation of Some Optimum Moisture and Binder Conditions for Coal Fines Briquetting. *J. S. Afr. Inst. Min. Metall.* **2015**, *115*, 329–333. [[CrossRef](#)]
15. Zhao, Y.; Qiu, J.; Ma, Z.; Sun, X. Eco-Friendly Treatment of Coal Gangue for Its Utilization as Supplementary Cementitious Materials. *J. Clean. Prod.* **2021**, *285*, 124834. [[CrossRef](#)]
16. Oluremi, J.R.; Elsaigh, W.H.A. Characterization of Coal Fines as Potential Supplementary Cementitious Additive for Remediation of Non-Polar Substance Contaminated Soil. *Mater. Today Proc.* **2023**, *86*, 24–31. [[CrossRef](#)]
17. Mutyavaviri, L.C.; Chihobo, C.H.; Makepa, D.C. The Ecological Effects and Valorization of Coal Fines—A Review. *Environ. Sci. Pollut. Res.* **2024**, *31*, 51045–51063. [[CrossRef](#)] [[PubMed](#)]
18. Ramudzwagi, M.; Tshiongo-Makgwe, N.; Nheta, W. Recent Developments in Beneficiation of Fine and Ultra-Fine Coal—Review Paper. *J. Clean. Prod.* **2020**, *276*, 122693. [[CrossRef](#)]
19. Chen, Y.; Ma, Z.; Ma, D.; Zhang, Z.; Li, W.; Yang, F.; Ji, Y.; Peng, T. Characteristics of the Coal Fines Produced from Low-Rank Coal Reservoirs and Their Wettability and Settleability in the Binchang Area, South Ordos Basin, China. *Geofluids* **2021**, *2021*, 1–17. [[CrossRef](#)]

20. Manyuchi, M.M.; Mbohwa, C.; Muzenda, E. Value Addition of Coal Fines and Sawdust to Briquettes Using Molasses as a Binder. *S. Afr. J. Chem. Eng.* **2018**, *26*, 70–73. [[CrossRef](#)]
21. Mangena, S.J.; De Korte, G.J.; McCrindle, R.I.; Morgan, D.L. The Amenability of Some Witbank Bituminous Ultra Fine Coals to Binderless Briquetting. *Fuel Process. Technol.* **2004**, *85*, 1647–1662. [[CrossRef](#)]
22. Kinnunen, P.H.M.; Kaksonen, A.H. Towards Circular Economy in Mining: Opportunities and Bottlenecks for Tailings Valorization. *J. Clean. Prod.* **2019**, *228*, 153–160. [[CrossRef](#)]
23. Kinnunen, P.; Karhu, M.; Yli-Rantala, E.; Kivikytö-Reponen, P.; Mäkinen, J. A Review of Circular Economy Strategies for Mine Tailings. *Clean. Eng. Technol.* **2022**, *8*, 100499. [[CrossRef](#)]
24. International Council on Mining and Metals. *Tailings Management*; International Council on Mining and Metals: London, UK, 2021.
25. De Korte, G.J. *Beneficiation of Fine Coal: Froth Flotation Efficiency*; Coaltech: Pretoria, South Africa, 2001.
26. De Korte, G.J. *Beneficiation of Weathered Coal*; Coaltech: Pretoria, South Africa, 2001.
27. Arnold, B.J. A Review of Element Partitioning in Coal Preparation. *Int. J. Coal Geol.* **2023**, *274*, 104296. [[CrossRef](#)]
28. Ferreira, L.P.; Müller, T.G.; Cargnin, M.; De Oliveira, C.M.; Peterson, M. Valorization of Waste from Coal Mining Pyrite Beneficiation. *J. Environ. Chem. Eng.* **2021**, *9*, 105759. [[CrossRef](#)]
29. Estiaty, L.M.; Fatimah, D. Widodo Bio-Coal Briquettes Using Low-Grade Coal. In *IOP Conference Series: Earth and Environmental Science*; Institute of Physics Publishing: Bristol, UK, 2018; Volume 118.
30. Armstrong, M.; Petter, R.; Petter, C. Why Have so Many Tailings Dams Failed in Recent Years? *Resour. Policy* **2019**, *63*, 101412. [[CrossRef](#)]
31. Klak, S. Carleton Perspectives on Public Policy 10 On the Brink of Better Tailings Management: Policy Options in the Aftermath of the Mount Polley Mine Disaster. *Carlet. Perspect. Public Policy* **2016**, *3*, 10–30.
32. Leonida, C. Turning the Tide on Tailings: Creating Opportunities Rather Than Risks. *Eng. Min. J.* **2023**. Available online: <https://www.e-mj.com/features/turning-the-tide-on-tailings-creating-opportunities-rather-than-risks/> (accessed on 10 May 2025).
33. Onalethata, S.; Raymond, S.; Konka, B. Fines Generation and Its Impacts at Morupule Underground Coal Mine, Botswana. In *Advances in Science, Technology and Innovation*; Springer Nature: Berlin/Heidelberg, Germany, 2024; pp. 465–468.
34. Marais, L.; Kemp, D.; van der Watt, P.; Matebesi, S.; Cloete, J.; Harris, J.; Ang Li Ern, M.; Owen, J.R. The Catastrophic Failure of the Jagersfontein Tailings Dam: An Industrial Disaster 150 Years in the Making. *Int. J. Disaster Risk Reduct.* **2024**, *109*, 104585. [[CrossRef](#)]
35. Adeeyo, R.O.; Edokpayi, J.N.; Volenzo, T.E.; Odiyo, J.O.; Piketh, S.J. Determinants of Solid Fuel Use and Emission Risks among Households: Insights from Limpopo, South Africa. *Toxics* **2022**, *10*, 67. [[CrossRef](#)] [[PubMed](#)]
36. Tatham, J. The Impact of Solid Cooking Fuels on the Health of Rural South African Households. Master's Thesis, University of Cape Town, Rondebosch, South Africa, 2021.
37. SASOL Limited. Climate Change Report. 2022. Available online: https://www.sasol.com/sites/default/files/2022-12/SASOL_CC%20Report%202022%20%202.pdf (accessed on 15 May 2025).
38. Marreiro, H.M.P.; Peruchi, R.S.; Lopes, R.M.B.P.; Andersen, S.L.F.; Eliziário, S.A.; Junior, P.R. Empirical Studies on Biomass Briquette Production: A Literature Review. *Energies* **2021**, *14*, 8320. [[CrossRef](#)]
39. Dinesha, P.; Kumar, S.; Rosen, M.A. Biomass Briquettes as an Alternative Fuel: A Comprehensive Review. *Energy Technol.* **2019**, *7*. [[CrossRef](#)]
40. Rawat, S.; Kumar, S. Critical Review on Processing Technologies and Economic Aspect of Bio-Coal Briquette Production. *Prep. Biochem. Biotechnol.* **2022**, *52*, 855–871. [[CrossRef](#)] [[PubMed](#)]
41. Adeleke, A.A.; Odusote, J.K.; Ikubanni, P.P.; Olabisi, A.S.; Nzerem, P. Briquetting of Subbituminous Coal and Torrefied Biomass Using Bentonite as Inorganic Binder. *Sci. Rep.* **2022**, *12*. [[CrossRef](#)] [[PubMed](#)]
42. Vaish, S.; Sharma, N.K.; Kaur, G. A Review on Various Types of Densification/Briquetting Technologies of Biomass Residues. *IOP Conf. Ser. Mater. Sci. Eng.* **2022**, *1228*, 012019. [[CrossRef](#)]
43. Shankar, J.; Christopher, T.; Wright, T.; Kenny, K.L.; Hess, J.R. A Review on Biomass Densification Technologies for Energy Application. *Biofuels Bioprod. Biorefinin* **2010**, *5*, 720.
44. Kaliyan, N.; Vance Morey, R. Factors Affecting Strength and Durability of Densified Biomass Products. *Biomass Bioenergy* **2009**, *33*, 337–359. [[CrossRef](#)]
45. Sokhansanj, S.; Turhollow, A.F. Biomass Densification—Cubing Operations and Costs for Corn Stover. *Appl. Eng. Agric.* **2004**, *20*, 495–499. [[CrossRef](#)]
46. Rahaman, S.A.; Salam, P.A. Characterization of Cold Densified Rice Straw Briquettes and the Potential Use of Sawdust as Binder. *Fuel Process. Technol.* **2017**, *158*, 9–19. [[CrossRef](#)]
47. Grover, P.D.; Mishra, S.K. *Regional Wood Energy Development Programme in Asia gcp/ras/154/net Food and Agriculture Organization of the United Nations Bangkok, Biomass Briquetting: Technology and Practices*; The FAO Regional Wood Energy Development Programme in Asia: Bangkok, Thailand, 1996.

48. Sundar, V.J.P.; D'Souza, P.M.; Donipati, J.V.; Kranthi, T. Development and Evaluation of a Screw Press Briquetting Machine for Biomass Fuel Production. *Int. J. Adv. Biochem. Res.* **2024**, *8*, 259–267. [[CrossRef](#)]
49. Ikubanni, P.P.; Agboola, O.O.; Olabamiji, T.S.; Adediran, A.A.; Anisere, T.; Oladimeji, S. Development and Performance Assessment of Piston-Type Briquetting Machine. In *IOP Conference Series: Earth and Environmental Science*; Institute of Physics Publishing: Bristol, UK, 2020; Volume 445.
50. Bembenek, M.; Zięba, A.; Kopyściański, M.; Krawczyk, J. Analysis of the Impact of the Consolidated Material on the Morphology of Briquettes Produced in a Roller Press. *J. Mater. Eng. Perform.* **2020**, *29*, 3792–3799. [[CrossRef](#)]
51. Aransiola, E.F.; Oyewusi, T.F.; Osunbitan, J.A.; Ogunjimi, L.A.O. Effect of Binder Type, Binder Concentration and Compacting Pressure on Some Physical Properties of Carbonized Corncob Briquette. *Energy Rep.* **2019**, *5*, 909–918. [[CrossRef](#)]
52. Mdhuli, F.T.; Harding, K.G. Comparative Life-Cycle Assessment of Maize Cobs, Maize Stover and Wheat Stalks for the Production of Electricity through Gasification vs Traditional Coal Power Electricity in South Africa. *Clean. Environ. Syst.* **2021**, *3*, 100046. [[CrossRef](#)]
53. Reddick, J.F.; Blottnitz, v.H.; Kothuis, B. A Cleaner Production Assessment of the Ultra-Fine Coal Waste. *J. S. Afr. Inst. Min. Metall.* **2007**, *107*, 811–816.
54. Edison Muzenda Potential Use of South African Coal Fines. In Proceedings of the ICMEME'2014, Abu Dhabi, United Arab Emirates, 19–20 March 2014.
55. 2023 Comprehensive Facts and Figures; Minerals Council South Africa. 2023. Available online: <https://www.mineralscouncil.org.za/industry-news/publications/facts-and-figures> (accessed on 3 May 2025).
56. Mangena, S.J.; du Cann, V.M. Binderless Briquetting of Some Selected South African Prime Coking, Blend Coking and Weathered Bituminous Coals and the Effect of Coal Properties on Binderless Briquetting. *Int. J. Coal Geol.* **2007**, *71*, 303–312. [[CrossRef](#)]
57. Olugbade, T.O.; Ojo, O.T. Binderless Briquetting Technology for Lignite Briquettes: A Review. *Energy Ecol. Environ.* **2021**, *6*, 69–79. [[CrossRef](#)]
58. Jia, J.; Wu, Y.; Zhao, D.; Li, B.; Wang, D.; Wang, F.; Chen, Y. Molecular Structure Characterization Analysis and Molecular Model Construction of Anthracite. *PLoS ONE* **2022**, *17*, e0275108. [[CrossRef](#)] [[PubMed](#)]
59. MMR. *Global Mined Anthracite Coal Market—Growth, Share, Trends, and Forecasts to 2023–2029*; Maximize Market Research: Maharashtra, India, 2023.
60. Department of Forestry, Fisheries and the Environment 2022/23. *Annual Report—Vote NO.32*. 2022. Available online: <http://www.dffe.gov.za/sites/default/files/reports/annualreport202223.pdf> (accessed on 3 May 2025).
61. Stafford, W.H.; De Lange, W.J. *Wood-Based Bio-Refineries: Value Adding to Sawmill Waste from the Forestry Industry*; Council for Scientific and Industrial Research, CSIR Research Space: Pretoria, South Africa, 2018.
62. Núñez-Retana, V.D.; Wehenkel, C.; Vega-Nieva, D.J.; García-Quezada, J.; Carrillo-Parra, A. The Bioenergetic Potential of Four Oak Species from Northeastern Mexico. *Forests* **2019**, *10*, 869. [[CrossRef](#)]
63. Srinivasan, G.R.; Mahajan, A.; Seth, R.; Mahajan, R. High Potential Organic Feedstocks for Production of Renewable Solid Briquettes—A Comprehensive Review. *Waste Manag. Circ. Econ.* **2023**, 231–277. [[CrossRef](#)]
64. Seroka, N.S.; Taziwa, R.; Khotseng, L. Sugar Cane Bagasse Ash: An Agricultural Residue with Potential Rubber Filler Applications. In *Application and Characterization of Rubber Materials*; IntechOpen: London, UK, 2023.
65. De, J.M.; Camargo, O.; Marcela, J.; Ríos, G.; Antonio, G.C.; Leite, J.T.C. Physicochemical Properties of Sugarcane Industry Residues Aiming at Their Use in Energy Processes. In *Sugarcane—Biotechnology for Biofuels*; IntechOpen: London, UK, 2021.
66. Mohlala, L.M.; Bodunrin, M.O.; Awosusi, A.A.; Daramola, M.O.; Cele, N.P.; Olubambi, P.A. Beneficiation of Corncob and Sugarcane Bagasse for Energy Generation and Materials Development in Nigeria and South Africa: A Short Overview. *Alex. Eng. J.* **2016**, *55*, 3025–3036. [[CrossRef](#)]
67. Kamusoko, R.; Mukumba, P. Potential of Wheat Straw for Biogas Production by Anaerobic Digestion in South Africa: A Review. *Energies* **2024**, *17*, 4662. [[CrossRef](#)]
68. Cui, X.; Yang, J.; Shi, X.; Lei, W.; Huang, T.; Bai, C. Pelletization of Sunflower Seed Husks: Evaluating and Optimizing Energy Consumption and Physical Properties by Response Surface Methodology (RSM). *Processes* **2019**, *7*, 591. [[CrossRef](#)]
69. Spirchez, C.; Lunguleasa, A.; Croitoru, C. Ecological Briquettes from Sunflower Seed Husk. *E3S Web Conf. EDP Sci.* **2019**, *80*, 01001. [[CrossRef](#)]
70. Sibulali, A. *Market Intelligence Report: Macadamia Nuts*; Western Cape Department of Agriculture: Elsenburg, Stellenbosch, South Africa, 2021.
71. Maingi, A.M.; Kiraithe, R.M.; Musau, S.K. Study of Combustion Characteristics of Macadamia Shells and Coffee Husks Briquettes in a Fixed Bed Reactor. *Mech. Eng.* **2023**. [[CrossRef](#)]
72. Vera, I.; Goosen, N.; Batidzirai, B.; Hoefnagels, R.; van der Hilst, F. Bioenergy Potential from Invasive Alien Plants: Environmental and Socio-Economic Impacts in Eastern Cape, South Africa. *Biomass Bioenergy* **2022**, *158*, 106340. [[CrossRef](#)]

73. Lusizi, Z.; Motsi, H.; Nyambo, P.; Elephant, D.E. Black (*Acacia Mearnsii*) and Silver Wattle (*Acacia Dealbata*) Invasive Tree Species Impact on Soil Physicochemical Properties in South Africa: A Systematic Literature Review. *Heliyon* **2024**, *10*, e24102. [CrossRef] [PubMed]
74. Rawat, Y.S.; Singh, G.S.; Tekleyohannes, A.T. Optimizing the Benefits of Invasive Alien Plants Biomass in South Africa. *Sustainability* **2024**, *16*, 1876. [CrossRef]
75. Costa, E.V.S.; Pereira, M.P.d.C.F.; da Silva, C.M.S.; Pereira, B.L.C.; Rocha, M.F.V.; Carneiro, A.d.C.O. Torrefied Briquettes of Sugar Cane Bagasse and Eucalyptus. *Rev. Arvore* **2019**, *43*, 231–277. [CrossRef]
76. Kumar, P.; Nandi, B.K. Impact of Wheat Straw and Petroleum Coke Blending on Combustion Behavior of High Ash Coal. *Energy Sources Part A Recovery Util. Environ. Eff.* **2023**, *45*, 3125–3137. [CrossRef]
77. Kumar, P.; Kumar Nandi, B. Combustion Characteristics of High Ash Indian Coal, Wheat Straw, Wheat Husk and Their Blends. *Mater. Sci. Energy Technol.* **2021**, *4*, 274–281. [CrossRef]
78. Nikiforov, A.; Kinzhibekova, A.; Prikhodko, E.; Karmanov, A.; Nurkina, S. Analysis of the Characteristics of Bio-Coal Briquettes from Agricultural and Coal Industry Waste. *Energies* **2023**, *16*, 3527. [CrossRef]
79. Lu, G.; Cheng, F.; Li, J. Enhancement of Coal Briquette Quality through Corn Stalk Blending and Binder Optimization. *Environ. Prog. Sustain. Energy* **2015**, *34*, 613–618. [CrossRef]
80. Bada, S.O.; Falcon, R.M.S.; Falcon, L.M.; Makhula, M.J. Thermogravimetric Investigation of Macadamia Nut Shell, Coal, and Anthracite in Different Combustion Atmospheres. *J. S. Afr. Inst. Min. Metall.* **2015**, *115*, 741–746. [CrossRef]
81. Keneilwe, R. *The South African Energy Sector Report*; Department of Mineral Resources and Energy: Pretoria, South Africa, 2022.
82. Industrial Policy Action Plan, 2018/19–2020/21. Department of Trade and Industry, 2018. Available online: <https://www.thedtic.gov.za/wp-content/uploads/publication-IPAP.pdf> (accessed on 18 May 2025).
83. Miao, Z.; Zhang, P.; Li, M.; Wan, Y.; Meng, X. Briquette Preparation with Biomass Binder. *Energy Sources Part A Recovery Util. Environ. Eff.* **2023**, *45*, 9834–9844. [CrossRef]
84. Butler, J.W.; Skrivan, W.; Lotfi, S. Identification of Optimal Binders for Torrefied Biomass Pellets. *Energies* **2023**, *16*, 3390. [CrossRef]
85. Oladeji, J.T. Theoretical Aspects of Biomass Briquetting: A Review Study. *J. Energy Technol. Policy* **2015**, *5*, 72–81.
86. Tumuluru, J.S.; Wright, C.T.; Hess, J.R.; Kenney, K.L. A Review of Biomass Densification Systems to Develop Uniform Feedstock Commodities for Bioenergy Application. *Biofuels Bioprod. Biorefining* **2011**, *5*, 683–707. [CrossRef]
87. Obi, O.F.; Pecenka, R.; Clifford, M.J. A Review of Biomass Briquette Binders and Quality Parameters. *Energies* **2022**, *15*, 2426. [CrossRef]
88. Zhong, Q.; Yang, Y.; Li, Q.; Xu, B.; Jiang, T. Coal Tar Pitch and Molasses Blended Binder for Production of Formed Coal Briquettes from High Volatile Coal. *Fuel Process. Technol.* **2017**, *157*, 12–19. [CrossRef]
89. Zhang, T.; Qiu, L.; Wang, Y.; Zhang, C.; Kang, K. Comparison of Bio-Oil and Waste Cooking Oil as Binders during the Codensification of Biomass: Analysis of the Pellet Quality. *BioEnergy Res.* **2019**, *12*, 558–569. [CrossRef]
90. Chinyere, D.C.; Asoegwu, S. *An Evaluation of Briquettes from Sawdust and Corn Starch Binder*; International Journal of Technology: Owerri, Nigeria, 2016.
91. Bello, R.S.; Olorunnisola, A.O.; Omoniyi, T.E.; Onilude, M.A. Performance of Briquettes Produced from Sawdust of Gmelina Arborea and Montmorillonite Clay as Binder. *Bioenergy Stud. Black Sea Agric. Res. Inst.* **2023**, *3*, 1–13. [CrossRef]
92. Das, R.; Mondal, M.K.; Pramanik, S. Comparison of Compressive Strength of Fly Ash Bonded Flue Dust Briquettes with That of Briquettes Made with Bentonite, Sodium Silicate, Lime, Starch, Pitch, Molasses and Dextrin Binder. *Trans. Indian Inst. Met.* **2023**, *76*, 1253–1262. [CrossRef]
93. Ikelle, I.I.; Ogbuagu, J.O.; Onuegbu, T.U. Effect of binders on the properties of coal briquette blends produced with different biomasses. *Ph.D. Thesis*; Nnamdi Azikwe University, AWKA, 2017. Available online: https://phd-dissertations.unizik.edu.ng/repos/81136571150_97363885380.pdf (accessed on 20 May 2025).
94. Mousa, E.; Ahmed, H.; Söderström, D. Potential of Alternative Organic Binders in Briquetting and Enhancing Residue Recycling in the Steel Industry. *Recycling* **2022**, *7*, 21. [CrossRef]
95. Han, H.; Duan, D.; Yuan, P. Binders and Bonding Mechanism for RHF Briquette Made from Blast Furnace Dust. *ISIJ Int.* **2014**, *54*, 1781–1789. [CrossRef]
96. Uwaoma, R.C.; Henning, C.N.; Bunt, J.R.; Leokaoke, N.T.; Neomagus, H.W.J.P. Comparison of Industrial Wastes as a Binder in the Agglomeration of Coal Fines. *Results Eng.* **2022**, *16*, 100729. [CrossRef]
97. Díaz-Cornejo, S.; Otero, M.C.; Banerjee, A.; Gordillo-Fuenzalida, F. Biological Properties of Exopolysaccharides Produced by *Bacillus* spp. *Microbiol. Res.* **2023**, *268*, 127276. [CrossRef] [PubMed]
98. Berekaa, M.M.; Ezzeldin, M.F. Exopolysaccharide from *Bacillus Mojavensis* DAS10-1; Production and Characterization. *J. Pure Appl. Microbiol.* **2018**, *12*, 633–640. [CrossRef]
99. Moghannem, S.A.M.; Farag, M.M.S.; Shehab, A.M.; Azab, M.S. Exopolysaccharide Production from *Bacillus Velezensis* KY471306 Using Statistical Experimental Design. *Braz. J. Microbiol.* **2018**, *49*, 452–462. [CrossRef] [PubMed]

100. Sánchez-León, E.; Huang-Lin, E.; Amils, R.; Abrusci, C. Production and Characterisation of an Exopolysaccharide by *Bacillus Amyloliquefaciens*: Biotechnological Applications. *Polymers* **2023**, *15*, 1550. [CrossRef] [PubMed]
101. Effendi, A.J.; Mastroiani, L.J.; Suhardi, S.H.; Ramadan, B.S. Potential Use of Extracellular Polymeric Substances (EPS) of *Bacillus Subtilis* for Biosorption of Mercury Produced from Soil-Washing Effluent. *Bioresour. Technol. Rep.* **2023**, *22*, 101481. [CrossRef]
102. Gratitude, C.; Patel, B.; Chigondo, M.; Rusere, M.; Maposa, M. Proof of Concept for Using Banana Waste Based Binders in Sawdust Briquetting: Comparative Studies between Raw and Carbonized Sawdust. *E3S Web Conf.* **2025**, *612*, 01003. [CrossRef]
103. Santos Pimenta, A. Charcoal Briquettes Produced with Recycled Coconut Pith. *Ciência Florest.* **2015**. Available online: <https://www.scielo.br/j/cflo/a/9hHMCWLTbfn85T3Pd6pkc9j/abstract/?lang=en> (accessed on 25 May 2025).
104. Deniz, V. Production of Water-Resistant Briquettes from a Mixture of an Imported Bituminous Coal and a Turkish Lignite with Copolymer Binder. *Int. J. Coal Prep. Util.* **2013**, *33*, 26–35. [CrossRef]
105. Dogbe, E.S.; Mandegari, M.; Görgens, J.F. Revitalizing the Sugarcane Industry by Adding Value to A-Molasses in Biorefineries. *Biofuels Bioprod. Biorefining* **2020**, *14*, 1089–1104. [CrossRef]
106. Blesa, M.J.; Miranda, J.L.; Izquierdo, M.T.; Moliner, R. Curing Temperature Effect on Mechanical Strength of Smokeless Fuel Briquettes Prepared with Molasses. *Fuel* **2003**, *82*, 943–947. [CrossRef]
107. Koskela, A.; Suopajarvi, H.; Fabritius, T. Interaction between Coal and Lignin Briquettes in Co-Carbonization. *Fuel* **2022**, *324*, 124823. [CrossRef]
108. Mardiyati, Y.; Tarigan, E.Y.; Prawisudha, P.; Shoimah, S.M.; Rizkiansyah, R.R.; Steven, S. Binderless, All-Lignin Briquette from Black Liquor Waste: Isolation, Purification, and Characterization. *Molecules* **2021**, *26*, 650. [CrossRef] [PubMed]
109. Ezéchiél, K.; Joel, T.K.; Abdon, A.; Roger, D.D. Accessibility and Effects of Binder Types on the Physical and Energetic Properties of Ecological Coal. *Heliyon* **2022**, *8*, e11410. [CrossRef] [PubMed]
110. Baba Hassan, A.; Okegbile, O.J.; Hassan, A.B.; Mohammed, A.; Irekeola, B.J. Effect of Starch and Gum Arabic Binders in the Combustion Characteristics of Briquette Prepared from Sawdust. *Artic. Int. J. Sci. Eng. Res.* **2014**, *5*. Available online: https://www.academia.edu/77921924/Effect_of_Starch_and_Gum_Arabic_Binders_in_the_Combustion_Characteristics_of_Briquette_Prepared_from_Sawdust (accessed on 25 May 2025).
111. Yan, L.; Liu, Q.Q.; Dong, H.S.; Wang, Y.F.; Li, J.; Zhong, X.; Wang, X.J.; Shi, Q. Manufacturing High-Performance Formcoke from Pulverized Coal Using Potato Residue-Based Biomass Binders. *Mater. Today Sustain.* **2022**, *20*, 100237. [CrossRef]
112. Sabah, E. Utilization of Waste Clay from Coal Preparation Tailings for Brick Production. *J. Ore Dress.* **2011**. Available online: https://www.academia.edu/10899111/Utilization_of_Waste_Clay_from_Coal_Preparation_Tailings_for_Brick_Production (accessed on 25 May 2025).
113. Botha, D.L.; Leokaoke, N.T.; Bunt, J.R.; Neomagus, H.W.J.P. Evaluation of Polymer Binders in Briquetting of Coal Fines for Combustion Applications. *J. South. Afr. Inst. Min. Metall.* **2021**, *121*, 113–118. [CrossRef]
114. Henning, C.; Leokaoke, N.; Bunt, J. Waanders FB Testing of Briquettes Made from Witbank Coal Fines with Polyvinyl Alcohol as Binder. In Proceedings of the 10th International Conference on Advances in Science, Engineering, Technology and Healthcare; Universal Researchers, Cape Town, South Africa, 19 November 2018.
115. Makgobebele, N.W.; Mbaya, R.K.K.; Bunt, J.R.; Leokaoke, N.T.; Neomagus, H.W.J.P. Evaluation of the Mechanical Properties of Wood-Derived Charcoal Briquettes for Use as a Reductant. *J. S. Afr. Inst. Min. Metall.* **2021**, *121*, 187–192. [CrossRef]
116. Chen, J.; Wu, J.; Yan, L.; Zhang, Y.; Guo, Z.; Xie, S.Y.; Li, J.; Yuan, L. The Effect of Alkalized Biomass on Pulverized Coal Molding and Carbonization of Bio-Briquette. *Mater. Today Sustain.* **2024**, *25*, 100626. [CrossRef]
117. Himbane, P.B.; Ndiaye, L.G.; Napoli, A.; Goli, T.; Rozis, J.F.; Ba, M.S.; Ndioukane, R. Influence of Binder Rate, Pyrolysis Temperature and Volume of Biochar Briquettes on CO and PM2.5 Emission Factors and Thermal Efficiency. *Energy Sustain. Dev.* **2022**, *68*, 525–531. [CrossRef]
118. Murakami, K.; Sato, S. Optimization of Mixing Ratios of Binders and Organic Matter for Charcoal Briquette Using Biochars Derived from Water Hyacinth. *Solid Fuel Chem.* **2024**, *58*, 226–231. [CrossRef]
119. Ferronato, N.; Calle Mendoza, I.J.; Gorrity Portillo, M.A.; Conti, F.; Torretta, V. Are Waste-Based Briquettes Alternative Fuels in Developing Countries? A Critical Review. *Energy Sustain. Dev.* **2022**, *68*, 220–241. [CrossRef]
120. Lohmeier, L.; Thaler, C.; Harris, C.; Wollenberg, R.; Schröder, H.W.; Brauer, A.S. Use of Bentonite and Organic Binders in the Briquetting of Particulate Residues from the Midrex Process for Improving the Thermal Stability and Reducibility of the Briquettes. *Steel Res. Int.* **2021**, *92*, 2100210. [CrossRef]
121. Yunusa, S.U.; Mensah, E.; Preko, K.; Narra, S.; Saleh, A.; Sanfo, S. A Comprehensive Review on the Technical Aspects of Biomass Briquetting. *Biomass Convers. Biorefinery* **2024**, *14*, 21619–21644. [CrossRef]
122. Singh, V.; Singh, A. Briquetting Technologies for Minerals and Metallurgical Applications: A Review. *Miner. Process. Extr. Metall. Rev.* **2025**, 1–20. [CrossRef]
123. Nurek, T.; Gendek, A.; Roman, K.; Dąbrowska, M. The Effect of Temperature and Moisture on the Chosen Parameters of Briquettes Made of Shredded Logging Residues. *Biomass Bioenergy* **2019**, *130*, 105368. [CrossRef]

124. Saeed, A.A.H.; Harun, N.Y.; Bilad, M.R.; Afzal, M.T.; Parvez, A.M.; Roslan, F.A.S.; Rahim, S.A.; Vinayagam, V.D.; Afolabi, H.K. Moisture Content Impact on Properties of Briquette Produced from Rice Husk Waste. *Sustainability* **2021**, *13*, 3069. [CrossRef]
125. Pang, L.; Yang, Y.; Wu, L.; Wang, F.; Meng, H. Effect of Particle Sizes on the Physical and Mechanical Properties of Briquettes. *Energies* **2019**, *12*, 3618. [CrossRef]
126. Setter, C.; Ataíde, C.H.; Mendes, R.F.; De Oliveira, T.J.P. Influence of Particle Size on the Physico-Mechanical and Energy Properties of Briquettes Produced with Coffee Husks. *Environ. Sci. Pollut. Res.* **2021**, *28*, 1–9. [CrossRef] [PubMed]
127. Zhou, H.; Bhattarai, R.; Li, Y.; Si, B.; Dong, X.; Wang, T.; Yao, Z. Towards Sustainable Coal Industry: Turning Coal Bottom Ash into Wealth. *Sci. Total Environ.* **2022**, *804*, 149985. [CrossRef] [PubMed]
128. Lv, B.; Luo, Z.; Fu, Y.; Zhang, B.; Qin, X.; Zhu, X. Particle Mixing Behavior of Fine Coal in Density Control of Gas–Solid Separation Fluidized Bed. *Particuology* **2020**, *50*, 76–87. [CrossRef]
129. Mani, T.; Murugan, P.; Abedi, J.; Mahinpey, N. Pyrolysis of Wheat Straw in a Thermogravimetric Analyzer: Effect of Particle Size and Heating Rate on Devolatilization and Estimation of Global Kinetics. *Chem. Eng. Res. Des.* **2010**, *88*, 952–958. [CrossRef]
130. Haidai, O.A.; Pavlychenko, A.V.; Koveria, A.S.; Ruskykh, V.V.; Lampika, T.V. Determination of granulometric composition of technogenic raw materials for producing composite fuel. *Nauk. Visnyk Natsionalnoho Hirnychoho Universytetu* **2022**, *4*, 52–58. [CrossRef]
131. Nati, C.; Spinelli, R.; Fabbri, P. Wood Chips Size Distribution in Relation to Blade Wear and Screen Use. *Biomass Bioenergy* **2010**, *34*, 583–587. [CrossRef]
132. Leokaoke, N.T.; Bunt, J.R.; Neomagus, H.W.J.P.; Waanders, F.B.; Strydom, C.A.; Mthombo, T.S. Manufacturing and Testing of Briquettes from Inertinite-Rich Low-Grade Coal Fines Using Various Binders. *J. S. Afr. Inst. Min. Metall.* **2018**, *118*, 83–88. [CrossRef]
133. Tamilvanan, A. Preparation of Biomass Briquettes Using Various Agro- Residues and Waste Papers. *J. Biofuels* **2013**, *4*, 47–55. [CrossRef]
134. Wang, X.D.; Xue, J.J.; Zhu, Y.J.; Liu, C.R.; Hu, X.Y.; Liang, H.; Dong, C.Q. The Study of Combustion Characteristics of Corn Stalks and Cobs via TGA-DTG-DSC Analysis. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *354*, 012130. [CrossRef]
135. Miao, M.; Deng, B.; Kong, H.; Yang, H.; Lyu, J.; Jiang, X.; Zhang, M. Effects of Volatile Matter and Oxygen Concentration on Combustion Characteristics of Coal in an Oxygen-Enriched Fluidized Bed. *Energy* **2021**, *220*, 119778. [CrossRef]
136. Imran, A.M.; Widodo, S.; Irvan, U.R. Correlation of Fixed Carbon Content and Calorific Value of South Sulawesi Coal, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *473*, 012106.
137. Adeleke, A.A.; Odusote, J.K.; Ikubanni, P.P.; Orhadahwe, T.A.; Lasode, O.A.; Ammasi, A.; Kumar, K. Ash Analyses of Bio-Coal Briquettes Produced Using Blended Binder. *Sci. Rep.* **2021**, *11*, 1–9. [CrossRef] [PubMed]
138. ASTM D3038-93; Standard Test Method for Drop Shatter Test for Coke. American Society for Testing and Materials: West Conshohocken, PA, USA, 1999.
139. BS EN ISO 17831-2:2015; Solid Biofuels-Determination of Mechanical Durability of Pellets and Briquettes. International Organization for Standardization: Geneva, Switzerland, 2015.
140. Richards, S.R. Physical Testing of Fuel Briquettes. *Fuel Process. Technol.* **1990**, *25*, 89–100. [CrossRef]
141. ISO 4700:2015; Iron Ore Pellets for Blast Furnace and Direct Reduction Feedstocks-Determination of the Crushing Strength. International Organization for Standardization: Geneva, Switzerland, 2015.
142. ASTM D3080/D3080M-23; Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions 1. ASTM: West Conshohocken, PA, USA, 2011.
143. ASTM D5865-07a; Test Method for Gross Calorific Value of Coal and Coke. ASTM International: West Conshohocken, PA, USA, 2019.
144. ASTM E871; Test Methods for Analysis of Wood Fuels. ASTM International: West Conshohocken, PA, USA, 2019.
145. ASTM D1102-84; Test Method for Ash in Wood. ASTM International: West Conshohocken, PA, USA, 2021.
146. ISO 14064; International Standard for GHG Emissions Inventories and Verification. International Organization for Standardization: Geneva, Switzerland, 2018.
147. Liu, Z.; Zhang, Y.; Zhong, L.; Orndroff, W.; Zhao, H.; Cao, Y.; Zhang, K.; Pan, W.P. Synergistic Effects of Mineral Matter on the Combustion of Coal Blended with Biomass. *J. Therm. Anal. Calorim.* **2013**, *113*, 489–496. [CrossRef]
148. Theron, J.A.; Le Roux, E. Representation of Coal and Coal Derivatives in Process Modelling. *J. S. Afr. Inst. Min. Metall.* **2015**, *115*, 339–349. [CrossRef]
149. The Presidency Just Energy Transition Implementation Plan (JET IP). 2024. Available online: https://justenergytransition.co.za/wp-content/uploads/2024/12/Just-Energy-Transition_Progress-Report-v2.pdf (accessed on 18 May 2025).
150. Acordi, J.; Simão, L.; Faraco, M.N.S.; Borgert, C.H.; Olivo, E.; Montedo, O.R.K.; Raupp-Pereira, F. Waste Valorization of Coal Mining Waste from a Circular Economy Perspective: A Brazilian Case Study Based on Environmental and Physicochemical Features. *Resour. Policy* **2023**, *80*, 103243. [CrossRef]

151. Chitranshi, J. *Global Coal Briquettes Market Overview*; Market Research Future: Pune, India, 2024.
152. Advancing the Future of Sustainable Coal;Coaltech 2025. Available online: <https://coaltech.co.za/wp-content/uploads/2025/02/Coaltech-Reasons-to-Join-our-Community.pdf> (accessed on 18 May 2025).

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