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# Bio-Briquettes Derived from Fibrous Agricultural and Softwood (FAS) Residues: A Review on Production Methods, Effects of Chemical Components, Utilization Potential, and Future Outlooks

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## Abstract

Fibrous agricultural and softwood (FAS) residues represent abundant lignocellulosic resources for bio-briquette production, yet their potential is strongly influenced by feedstock characteristics, chemical composition, processing conditions, and application requirements. A structured narrative review of 106 publications was conducted to synthesize these interrelationships and identify development prospects. FAS bio-briquette performance is governed by interactions between feedstock composition and processing conditions, with lignocellulosic fractions and ash-forming minerals determining the balance among mechanical integrity, energy performance, and combustion behavior. Various FAS residues, including rice husk and straw, corn cob, sugarcane bagasse, coconut and oil palm residues, cocoa pod shell, fruit and nut residues, pine residues, and softwoods have been investigated under diverse processing conditions. Reported properties varied widely with densities of 0.30–1.32 g/cm$^3$, calorific values of 12.41–31.51 MJ/kg, moisture contents (MC) of 0.3–29.72%, ash contents of 0.1–59.2%, volatile matter (VM) of 0.9–90.7%, fixed carbon (FC) of 22.97–81.73%, compression strength of 0.004–21.75 MPa, ignition times of 10.25–106 s, burning rates of 0.119–5.85 g/s, and burning times of 23.88–84 min, while shatter resistance >99% and shatter indices 0.56–2.49%. Beyond domestic cooking and heating, FAS bio-briquettes show potential for coal co-firing, metallurgical reduction, and construction-material applications through ash utilization, although suitability depends on application-specific trade-offs. Future development should prioritize feedstock-specific optimization, scalable production, techno-economic and life-cycle assessment, and standardized quality and sustainability criteria for reliable commercialization.

***Keywords:*** *bio-briquette, briquetting technology, fibrous biomass waste, softwood residues*

## 1. Introduction

The global transition towards low-carbon energy systems has accelerated the development of renewable and sustainable alternatives to fossil fuels in response to increasing energy demand, climate change, and concerns over greenhouse gas (GHG) emissions [1]. Among the various renewable energy resources, biomass has attracted considerable attention owing to its widespread availability, renewability, and potential to convert abundant organic residues into valuable energy products. In particular, bio-briquettes have emerged as one of the most promising solid biofuels because densification improves the energy density, handling, transportation, storage, and combustion performance of raw biomass [2]. Consequently, bio-briquette technology has become an effective approach for valorizing biomass residues while supporting resource efficiency and circular bioeconomy strategies. Beyond their conventional role have also attracted growing interest in broader industrial applications.

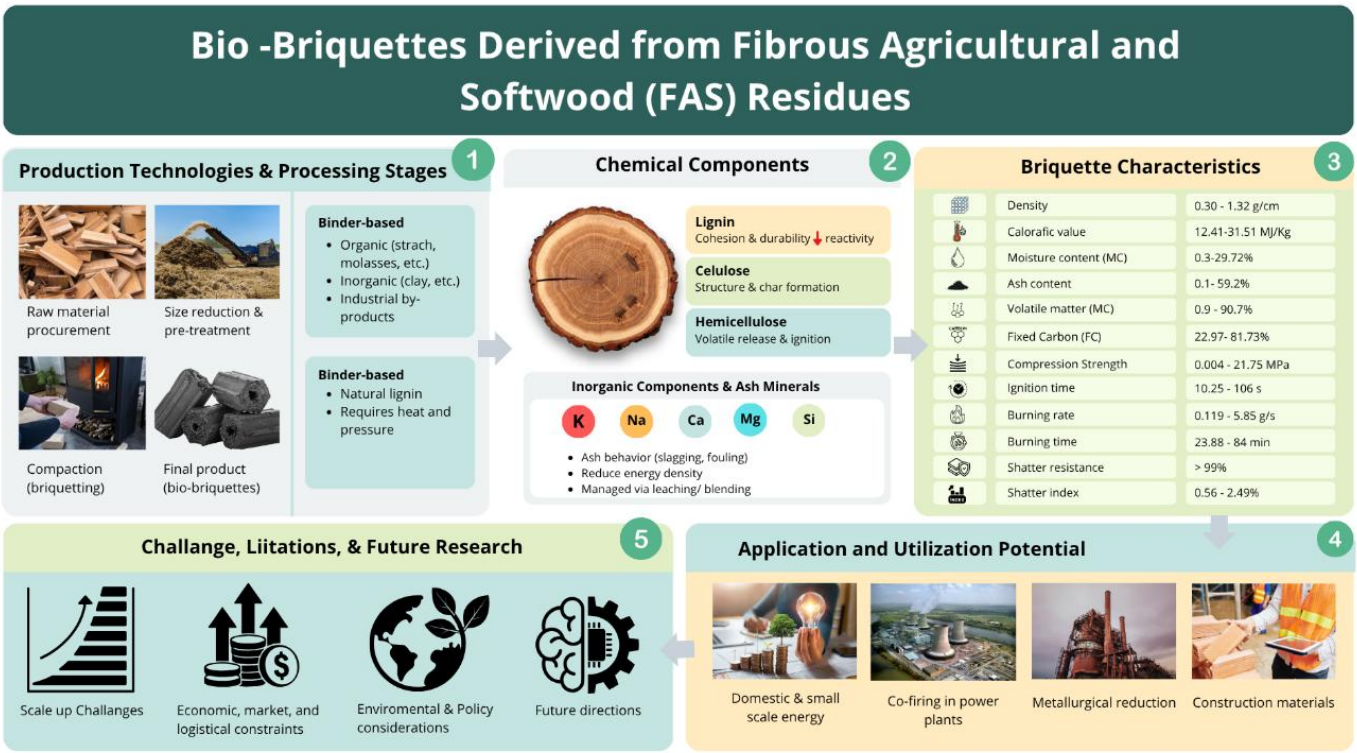



**Figure 1.** Overview of FAS-derived bio-briquettes.

Biomass residues utilized for bio-briquette production are generally classified into agricultural by-products and residues, forestry by-products and residues, and industrial biomass processing wastes [3]. Rather than being openly burned or disposed of as waste, these biomass resources can be converted into densified solid products with improved fuel quality and broader utilization potential. Among the available biomass resources, Fibrous Agricultural and Softwood (FAS) residues represent one of the most abundant and promising lignocellulosic feedstocks because of their high availability, relatively low cost, and favourable physicochemical properties [4]. The quality and performance of bio-briquettes are governed not only by feedstock characteristics but also by production technologies, interactions among chemical composition, and operating conditions. Variations in ellulose, hemicellulose, lignin, extractives, ash, and moisture contents (MC) considerably influence densification, mechanical strength, density, calorific value, and combustion characteristics. Likewise, pretreatment strategies, binder selection, compaction pressure, and briquetting temperature significantly affect the physical and fuel properties of the resulting bio-briquettes [5,6]. Therefore, understanding the relationships among feedstock characteristics, chemical composition, and processing parameters is essential for optimizing bio-briquette quality and their utilization.

Although numerous review articles have discussed biomass briquetting technologies, biomass-derived solid

fuels, or specific lignocellulosic feedstocks, these studies generally address individual aspects such as feedstock characteristics, densification techniques, combustion performance, or end-use applications separately. A comprehensive review systematically integrates production technologies, the effects of chemical composition and operating conditions, comparative feedstock characteristics, diverse utilization pathways, and future development strategies specifically for bio-briquettes derived from FAS residues remain limited [7,8]. Therefore, this review provides a comprehensive overview of bio-briquettes derived from FAS residues by systematically discussing production technologies, followed by the influence of chemical composition, summarizes the current and emerging utilization pathways, and discusses the major technical challenges together with emerging innovations and future research directions to support the sustainable large-scale development of FAS derived bio-briquettes. An integrated overview of FAS-derived bio-briquettes, relationships among production technologies, chemical components, briquette characteristics, utilization potential, and future research directions shown in Fig. 1.

## 2. Results and Discussion

### 2.1. Briquette production technologies and processing stages

#### 2.1.1. Overview of conventional and advanced briquetting technology

Early briquetting practices relied on manual compaction methods that offered limited pressure and inconsistent product quality. Briquette production generally involves three main stages, namely procurement of biomass raw materials, processing, and compaction as illustrated in Fig. 2 [9]. With growing demand for standardized bio-briquettes, mechanized briquetting systems were introduced to improve compaction efficiency, throughput, and uniformity. Among these, piston press technology became widely adopted due to its ability to generate high compressive forces suitable for fibrous and coarse biomass. The reciprocating action of the piston allows the production of dense and cylindrical briquettes with relatively low energy consumption [10]. Screw extruders represent another major technological development, offering continuous operation, higher temperature generation due to friction, and the ability to produce briquettes with superior structural integrity and enhanced combustibility [9,11]. Roller compaction technologies, although traditionally used for fine powders, have also been adapted for biomass densification, producing uniform pillow-shaped briquettes through controlled nip pressure between rotating rollers [9,12].

The efficiency and product characteristics of briquetting technologies vary significantly depending on FAS type. Piston presses are generally more tolerant of variations in particle size and MC, making them suitable for coarse and fibrous biomass residues. Studies have demonstrated that effective briquetting can still be achieved with different hammer mill screen sizes (19.05, 25.40, and 31.75 mm), suggesting that piston presses are relatively insensitive to particle size variations [13]. Screw extruders, in contrast, are more effective for homogenized and fine-particle biomass due to their reliance on continuous screw–barrel interaction to generate heat and activate natural binders [11]. Roller presses require more uniform feedstock preparation but are capable of producing briquettes at high throughput, which is advantageous for large-scale operations [14]. Mechanical piston press consists of a ram (piston) and it is driven by an electric motor, while screw press consists of a screw extruder, although roller press consists of dual cylindrical rollers of the same diameter which rotating horizontally in opposite directions on parallel axes as shown in Fig. 3 [9]. Across these technologies, the resulting density output, mechanical durability, and energy conversion performance are strongly influenced by operating pressure, temperature generation, and feedstock compatibility.

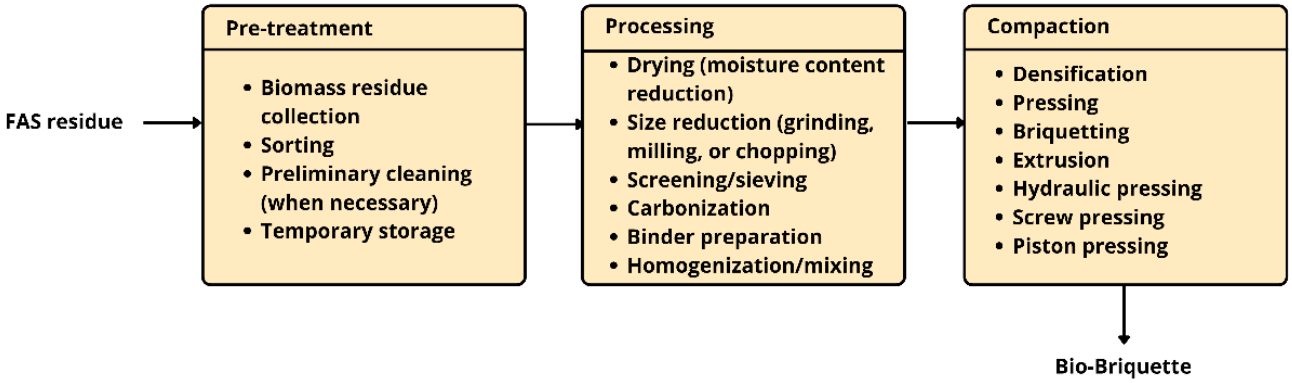



**Figure 2.** Principal briquette production process.

Recent advancements have introduced thermochemical pre-conditioning within the briquetting process to further enhance durability and energy

performance. Torrefaction-assisted briquetting has emerged as a promising route, in which biomass undergoes mild pyrolysis (220–300°C) with oxygen ($O_2$) concentration 0–21% to improve hydrophobicity, reduce moisture uptake, and increase grindability prior to densification [15]. The transformation of biomass properties because of torrefaction is graphically presented in Fig. 4. The typical energy content of the torrefied products is solid (70-90%), liquid (5-10%), and gases (5-15%) [16]. Similarly, carbonized briquetting techniques where feedstock is partially carbonized before compaction produce briquettes with higher fixed carbon (FC) content, lower volatile matter (VM), and improved performance as solid fuel or metallurgical reducing agents. Such advanced methods demonstrate substantial potential for upgrading low-quality FAS residues into high-value briquettes suitable for both energy and non-energy applications [17]. Together, these technological developments mark a

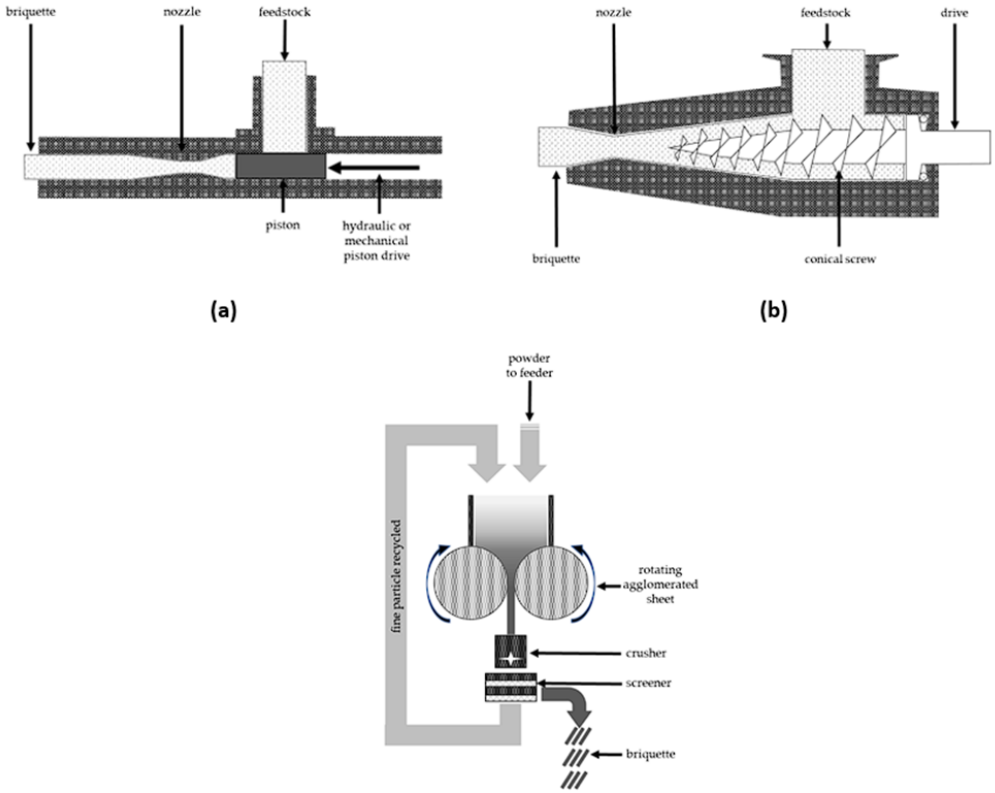



**Figure 3.** Schematic illustration of common briquetting presses: (a) piston press, (b) screw press, and (c) roller press [9].

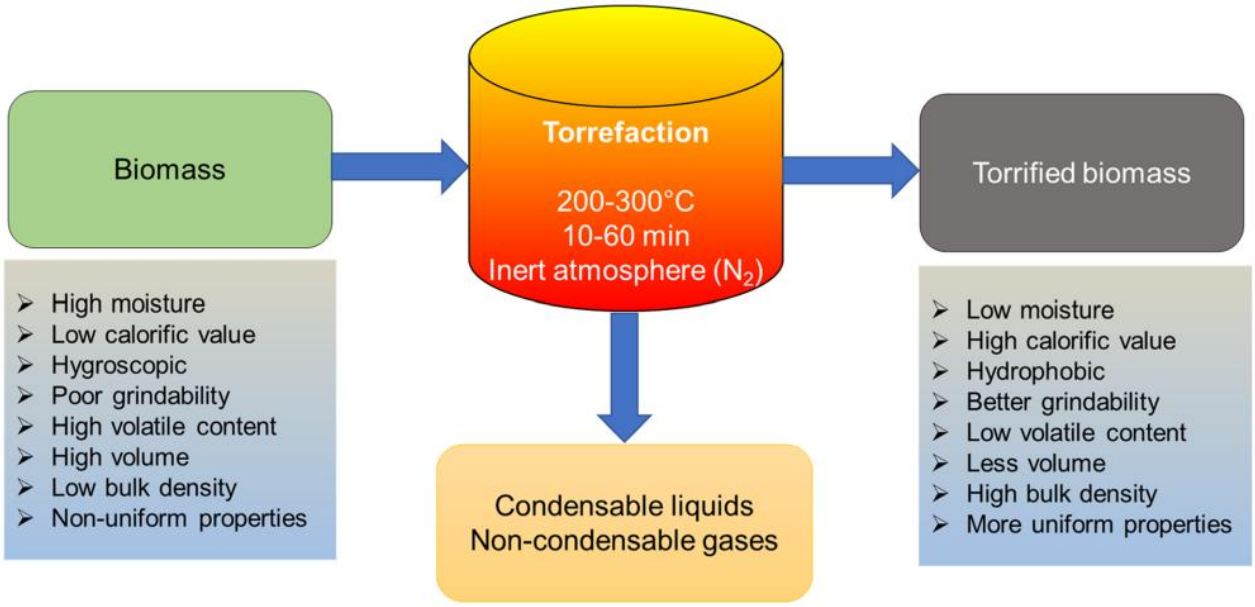



**Figure 4.** Distinction between raw biomass and torrefied biomass [16].

significant evolution from simple manual compaction toward engineered briquetting systems designed to optimize material performance, process efficiency, and end-use versatility.

#### 2.1.2. Pre-treatment processes

Due to their inherently high MC, fibrous morphology, and variable particle geometry, FAS residues generally require pre-treatment to improve compressibility, dimensional stability, and fuel quality prior to briquetting. Excessive MC not only generates steam during compression but also dissipates frictional heat, thereby limiting lignin softening and weakening inter-particle bonding. As a result, briquettes become more prone to swelling, cracking, and dimensional instability during storage and handling. Conversely, maintaining an optimum MC improves compaction efficiency, mechanical durability, and storage stability [18,19]. Particle size reduction through milling or shredding further enhances densification by increasing surface contact between particles and promoting more uniform packing. The resulting increase in particle size uniformity facilitates more uniform stress distribution during densification, leading to improved packing efficiency and briquette integrity [20]. Nevertheless, the degree of size reduction should be carefully controlled because the optimum particle size varies with feedstock characteristics and processing conditions. For example, past research demonstrated that varying the particle size of sawdust–rice husk carbon mixtures (250–2000 μm) significantly affected the compaction behavior of the feedstock, indicating that particle size optimization is an essential pre-treatment step rather than a universally fixed parameter [21]. Therefore, appropriate control of moisture content and particle size establishes favorable feedstock characteristics for efficient densification and consistent briquette production.

In addition to conventional feedstock preparation, several advanced pre-treatment strategies have been adopted to further improve the suitability of FAS residues for briquetting. Among these are torrefaction and steam explosion to modify biomass structure prior to densification [22–24]. For instance, torrefaction partially degrades hemicellulose while largely preserving cellulose and lignin, and simultaneously removes bound moisture, producing a more hydrophobic, brittle, and energy-dense biomass. These physicochemical changes improve grindability, facilitate subsequent milling and densification processes, and ultimately enhance the handling and fuel quality of FAS residues prior to briquetting [22,23]. Steam explosion employs high-pressure steam followed by rapid decompression to disrupt the lignocellulosic fiber network and modify the cell wall structure, resulting in improved compressibility and lower mechanical energy requirements during densification [24]. Compared with conventional drying and particle size reduction, these advanced pre-treatment methods offer greater control over biomass physicochemical properties, although their implementation requires additional processing costs and energy input. Consequently, the selection of an appropriate pre-treatment strategy should consider the intrinsic characteristics of FAS residues alongside the desired briquette quality and production economics.

#### 2.1.3. Briquetting methods: binder-based and binderless techniques

Briquetting methods are broadly categorized into binder-based and binderless techniques, with the selection primarily determined by the physicochemical characteristics of FAS residues, particularly lignin content, MC, and fiber morphology. Binder-based briquetting incorporates a wide range of organic, inorganic, and industrial by-product binders to enhance inter-particle adhesion and improve briquette integrity, making it suitable for feedstocks with limited natural binding ability such as rice husk, bagasse, and some agricultural fibers. Although binders improve mechanical stability and reduce friability, their use increases production costs and may alter ash content and combustion characteristics [25,26].

In contrast, binderless briquetting relies on the thermoplastic behavior of natural lignin, which softens at approximately 140–180°C under elevated pressure to form strong inter-particle bonds without chemical additives. Consequently, this method is particularly effective for FAS with relatively high lignin contents. The bonding mechanism in binderless briquetting has been explained through several complementary theories, including the capillary, adhesion molecule, bituminous, humic acid, colloid, and denser water theories [27]. Collectively, these theories describe the roles of MC, intermolecular attraction, softened organic constituents, and physicochemical interactions in promoting particle bonding during densification, indicating that binderless briquetting is governed by multiple simultaneous mechanisms rather than a single bonding phenomenon.

Regardless of the briquetting method, product quality is strongly governed by processing parameters, particularly compaction pressure, temperature, and dwell time. Increasing compaction pressure generally enhances particle rearrangement, reduces void spaces, and improves briquette density and mechanical strength [28]. Likewise, appropriate compaction temperatures promote lignin softening and facilitate bond formation, whereas excessive temperatures may initiate thermal degradation of lignocellulosic components, particularly above approximately 200°C, thereby compromising briquette integrity [29]. Dwell time also plays an important role by

allowing stress relaxation and stabilization of newly formed inter-particle bonds before pressure release [30]. Since the optimum combination of these parameters varies with feedstock characteristics, process optimization is essential to achieve consistent densification efficiency and briquette quality.

#### 2.1.4. Process optimization parameters

Process optimization is essential because briquette quality is governed by the combined effects of multiple processing variables rather than by any single parameter alone. Compaction pressure, temperature, MC, particle size, and dwell time interact to determine feedstock compressibility, particle bonding, and densification behavior. To capture these interactions, recent studies increasingly employ multivariable optimization techniques instead of varying individual parameters independently. Conventional approaches, including Response Surface Methodology (RSM), Central Composite Design (CCD), and regression-based models, remain widely used because they efficiently quantify parameter interactions while substantially reducing the number of experimental trials [31]. More recently, machine-learning models such as Artificial Neural Networks (ANN) have demonstrated considerable potential for predicting briquette properties from complex datasets and identifying optimal operating conditions with higher predictive accuracy than conventional empirical models [32]. These complementary optimization strategies provide a practical framework for tailoring briquetting conditions to the diverse physicochemical characteristics of FAS residues, thereby improving process efficiency, and product quality.

### 2.2. Influence of chemical components of fibrous agricultural and softwood (FAS) residue

#### 2.2.1. Role of lignin, cellulose, and hemicellulose

The relative proportions of lignin, cellulose, and hemicellulose substantially influence the mechanical and energetic characteristics of FAS-derived bio-briquettes. Lignin plays a major role in structural cohesion and generally favors higher mechanical strength and durability, making lignin-rich softwood residues particularly suitable for producing robust briquettes. Its relatively high carbon content also contributes to the energy characteristics of the resulting fuel [33]. Cellulose primarily provides structural rigidity through its highly ordered polymeric structure and contributes to the formation of VM and char during thermal conversion, thereby affecting briquette integrity [34]. Hemicellulose being more thermally reactive than cellulose and lignin, decomposes more readily and contributes substantially to volatile release, which can promote ignition and combustion reactivity but may also reduce structural stability when extensively degraded [35]. Overall, the relative balance among these three components determines the trade-off between mechanical stability and thermal reactivity, with lignin predominantly supporting cohesion and durability, cellulose contributing to structural rigidity and fuel formation, and hemicellulose influencing volatile release and combustion behavior. Their combined composition therefore provides an important chemical basis for explaining variations in the quality and fuel performance of FAS-derived bio-briquettes. The relationships described above indicate that cellulose, hemicellulose, and lignin affect briquette performance through different but interconnected mechanisms. To provide a more systematic comparison, Table 1 summarizes the principal effects of each lignocellulosic component on densification, mechanical strength, VM, FC formation, ignition, and combustion behavior.

**Table 1.** Correlation of lignocellulosic components with bio-briquette performance.

| Feedstock | Densification | Mechanical Strength | VM | FC | Ignition | Combustion | Ref. |
|---|---|---|---|---|---|---|---|
| Cellulose | Enhance density | Enhance strength | Increase VM | Forms FC | Rapid release | Decomposes at 240–360°C | [6,36–38] |
| Hemicellulose | Enhance compaction | Enhance strength | Increase VM | Produce less FC | Promotes early ignition | Decomposes at 130–260°C | [6,36–38] |
| Lignin | Enhance durability | Enhance strength | Decrease VM | Increase FC | Raises ignition temperature | Decomposes at 280–500°C | [6,36–38] |

Overall, the three lignocellulosic components contribute differently to briquette performance, with cellulose and hemicellulose being more closely associated with structural integrity and volatile release, whereas lignin favors bonding, char formation, and sustained combustion. These relationships help explain the performance variations observed among FAS feedstocks with different lignocellulosic compositions.

#### 2.2.2. Impact of inorganic components and ash forming minerals

Inorganic components, particularly potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), and silicon (Si) substantially influence the ash characteristics and combustion behavior of FAS-derived bio-briquettes. Alkali

metals such as Na and K can volatilize at elevated temperatures and react with silicates and other ash-forming elements to form low-melting compounds, promoting slagging and fouling. Although refuse-derived fuel (RDF), a processed fuel derived from combustible fractions of solid waste, differs from FAS residues in feedstock composition, similar mineral interactions have been observed in coal–RDF co-combustion, where Na and K concentrations reached 4.02 and 0.22 ppm, respectively, at 90% RDF; the nonlinear Na release was attributed to competing effects of ferric oxide ($Fe_2O_3$) which promoted volatilization, while silica ($SiO_2$) and aluminum oxide ($Al_2O_3$) which suppressed it [39]. Silicon-rich residues, such as rice husk, generally produce high-ash briquettes dominated by $SiO_2$ up to 97%; however, the resulting ash behavior depends not only on Si abundance but also on its interactions with alkali and alkaline-earth elements (AAEM). for example, removing AAEM, particularly K, increased the crystallization temperature of $SiO_2$, demonstrating that K–$SiO_2$ interactions affect mineral transformation during heating [40,41]. This interaction is relevant to FAS briquette combustion because changes in mineral transformation can alter ash fusion and deposition behavior. Similarly, Ca and Mg can alter ash mineralogy, with their effects on mineral stability depending on the overall elemental composition. Biomass ash studies have identified Ca–Mg as a distinct mineral association, indicating that their effects on ash fusion and deposition depend on the specific mineral phases formed rather than on elemental abundance alone [42]. These variations indicate that elemental concentrations alone may not adequately predict ash behavior. High ash content additionally reduces the energy density of briquettes by diluting their combustible fraction, whereas ash mineral composition governs the severity of combustion-related deposition and fusion problems. These ash-related issues can be mitigated through feedstock management strategies, water or mild-acid leaching removes soluble AAEM, while blending high-ash residues with low-ash feedstocks dilutes problematic ash-forming elements and improves the overall ash composition [43]. Therefore, both ash quantity and mineral composition should be considered when evaluating FAS residues and selecting suitable feedstock combinations for bio-briquette production.

#### 2.2.3. Characteristic outcomes and quality metrics

The quality of FAS-derived bio-briquettes can be evaluated through a combination of physical, mechanical, proximate, elemental, and energetic characteristics, including MC, bulk and particle density, mechanical durability, VM, ash content, FC, elemental composition, and calorific value [44,45]. Standardized analytical methods provide a consistent basis for evaluating these properties, with American Standard Test Method (ASTM) including ASTM E871-82(2019) for MC, ASTM E872-82(2019) for VM, ASTM E1534-93(2019) for ash content of particulate wood fuels, ASTM E873-20 for bulk density of densified particulate biomass fuels, and ASTM E870-82(2019) for broader analysis of wood fuels [46]. Corresponding International Organization for Standardization (ISO) methods include ISO 18134-1:2022 for MC, ISO 18122:2022 for ash, ISO 18123:2023 for VM, ISO 18125:2017 for calorific value, ISO 17828:2025 for bulk density, ISO 18847:2024 for particle density of pellets and briquettes, and ISO 17831-2:2025 for mechanical durability of briquettes [47]. Chemical characterization can additionally employ ISO 16948:2015 for total C, H, and N; ISO 16994:2026 for S and Cl; ISO 16967:2015 for major ash-forming elements such as Al, Ca, Fe, Mg, P, K, Si, Na, and Ti; and ISO 16968:2015 for minor elements [6,47]. For quality classification, ISO 17225-1:2021 provides the general framework for solid biofuels, while ISO 17225-3:2021 and ISO 17225-7:2021 specifically establish fuel specifications and quality classes for graded wood and non-woody briquettes respectively [47]. In Indonesia, SNI 01-6235-2000 may also be referenced for wood charcoal briquettes, although its scope should be distinguished from that of biomass solid-fuel standards [45]. Collectively, these methods and classification standards provide a comprehensive framework for relating the physicochemical characteristics of FAS briquettes to their mechanical integrity, combustion performance, and intended fuel application.

### 2.3. Feedstock diversity of FAS residue

#### 2.3.1. Classification and sources of FAS residue

FAS residue encompasses a broad range of lignocellulosic materials generated from agricultural production, agro-industrial processing, and wood-processing activities. Fibrous agricultural residues include crop residues such as rice husk, rice straw, corn stover, corn cob, sugarcane bagasse, coconut husk, coconut coir, coconut shell, oil palm empty fruit bunches (EFB), fronds fiber, mesocarp fiber, coffee husk, cocoa pod shells, fruit peels, and other fibrous plant residues. These materials may originate from either primary agricultural activities or downstream processing of agricultural commodities and can be used individually or in blends to tailor briquette properties [48]. Softwood residues in contrast, primarily comprise wood-processing and forestry residues such as sawdust, wood chips, bark, cones, needles, and other residues from *Pinus*, *Picea*, *Larix,* and related softwood species [49].

The suitability of these feedstocks for briquetting is governed by their inherent lignocellulosic composition, mineral content, MC, particle morphology, and thermal

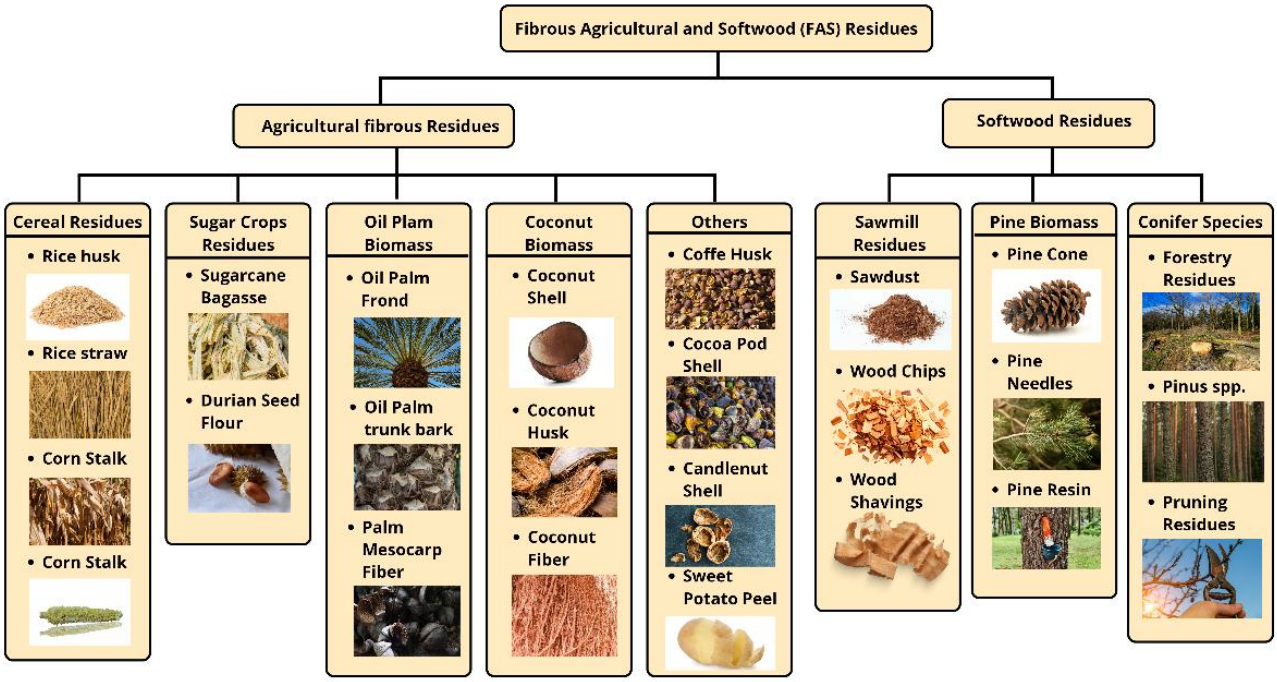



**Figure 5.** Classification of representative fibrous agricultural and softwood (FAS) residues used as feedstocks for bio-briquette production.

behavior which vary substantially among species and residue types. Accordingly, FAS residues should not be treated as a chemically uniform feedstock class; rather, their diversity provides opportunities to select, blend, and pretreat materials according to the targeted density, mechanical integrity, combustion characteristics, and energy performance of the resulting bio-briquettes. Fig. 5 presents the classification of representative FAS residues discussed throughout this review. This classification provides an overview of the principal feedstock groups that form the basis for the subsequent discussions on production technologies, feedstock characteristics, bio-briquette performance, and utilization pathways.

### 2.3.2. Comparative analysis of bio-briquettes performance

Bio-briquette performance varies substantially among FAS feedstocks and processing configurations because feedstock composition interacts with pretreatment, particle size, binder type and concentration, compaction pressure, and thermal processing. Reported performance therefore spans a wide range of density, mechanical strength or durability, MC, VM, ash content, FC, calorific value, and combustion behavior. Because pretreatment can substantially modify biomass composition and fuel properties, the materials in Table 1 are distinguished as raw biomass (RB), biochar-based materials (BBM), thermally pretreated materials (TPM), and biomass–coal mixtures (BCM) to facilitate more appropriate interpretation of the reported performance. Feedstock selection determines the initial material characteristics, whereas processing conditions and formulation determine how these characteristics are translated into final briquette performance. Table 2 summarizes the feedstock, material type, process, and performance of FAS-derived bio-briquettes.

**Table 2.** Feedstock types, operating conditions, and performance characteristics of bio-briquettes from FAS residue.

| Feedstock | Material Types | Operating Conditions | Performance | Ref. |
|---|---|---|---|---|
| Durian peels (+ tapioca starch binder) | BBM | 7 d initial sun-dried; drum carbonization 5 h; sieved to 28 mesh; tapioca binder (1:5); manual pressing 18 kN/m$^2$ for 2 min; 5 d final sun-dried | Density 1137.91 kg/m$^3$, drop test 0%, gross calorific value (GCV) 21.09 MJ/kg, and sulfur (S) 0.16% | [50] |
| Durian peels + rice husk (3:1) (+ tapioca starch binder) | BBM | Drum carbonization 5 h; sieved to 28 mesh; tapioca binder (1:5); manual pressing 18 kN/m$^2$ for 2 min; 5 d final sun-dried | Density 840.64 kg/m$^3$, drop test 0.35%, GCV 22.86 MJ/kg, and S 0.15% | [50] |

| Feedstock | Material Types | Operating Conditions | Performance | Ref. |
|---|---|---|---|---|
| Durian peels + coconut shell (1:3) (+ tapioca starch binder) | BBM | Drum carbonization 5 h; sieved to 28 mesh; tapioca binder (1:5); manual pressing 18 kN/m$^2$ for 2 min; 5 d final sun-dried | Density 1181.79 kg/m$^3$, drop test 0.25%, GCV 26.24 MJ/kg, and S 0.07% | [50] |
| Rice husk | BBM | 4 d initial sun-dried; drum carbonization 5 h; sieved to 28 mesh; tapioca binder (1:5); manual pressing 18 kN/m$^2$ for 2 min; 5 d final sun-dried | Density 1324.56 kg/m$^3$, drop test 0.22%, GCV 12.41 MJ/kg, and S 0.07% | [50] |
| Rice husk (+ cassava starch binder) | RB | Sieved to 1–2 mm; binder 5–15%; dwell time 0.5–1.5 min | Relaxed density 0.306 g/cm$^3$, compression strength (CS) 0.19 MPa, boiling time 5.10 min, and $CO_2$ emission 1.90% | [51] |
| Rice husk (+ locust bean pulp binder) | RB | Sieved to 1–2 mm; binder 5–15%; dwell time 0.5–1.5 min | Relaxed density 0.300 g/cm$^3$, CS 0.41 MPa, boiling time 9.3 min, and $CO_2$ emission 2.16% | [51] |
| Rice husk (+ sweet potato peel binder) | RB | Sieved to 1–2 mm; binder 5–15%; dwell time 0.5–1.5 min | Relaxed density 0.295 g/cm$^3$, CS 0.24 MPa, boiling time 6.8 min, and $CO_2$ emission 2.89% | [51] |
| Rice husk + coffee husk (+ gum arabic binder) | BBM | 2 d sun-dried; drum carbonized at 300–350℃ for 9 h; sieved to 2 mm; gum arabic binder 6.9%; pressed at ≤7 MPa | Density 15.81 kg/m$^3$, CS 0.008 MPa, GCV 18.665 MJ/kg, boiling time 47 min, MC 8.1%, VM 31.5%, ash 22.9%, and FC 37.2% | [52] |
| Rice husk + coffee husk (+ clay binder) | BBM | 2 d sun-dried; drum carbonized at 300–350℃ for 9 h; sieved to 2 mm; clay binder 5.8%; pressed at ≤7 MPa | Density 16.55 kg/m$^3$, CS 0.004 MPa, GCV 17.156 MJ/kg, boiling time 45 min, MC 9.5%, VM 35.2%, ash 11.5%, and FC 43.6% | [52] |
| Rice husk + coffee husk (+ gum arabic and clay binder) | BBM | 2 d sun-dried; drum carbonized at 300–350℃ for 9 h; sieved to 2 mm; gum arabic + clay binder 13%; pressed at ≤7 MPa | Density 17.5 kg/m3, CS 0.012 MPa, GCV 17.404 MJ/kg, boiling time 56 min, MC 7.4%, VM 30.4%, ash 26.8%, and FC 35.3% | [52] |
| Rice husks (+ sugarcane molasses binder) | BBM | Biochar 100 wt%; molasses binder 35 wt%; sieved to 1.5 mm; screw-extruded; combusted at 0.02–0.6 kg/m$^2$s air-mass flux | Density 1057.96 kg/m$^3$, GCV 22.66 MJ/kg, Carbon (C) 32.88 wt%, Oxygen (O) 61.70 wt%, MC 8%, ash 48.73%, VM 20.30%, and FC 22.97% | [53] |
| Rice husk + coconut husk + sawdust (+ cassava starch binder) | BBM | MFGS carbonized at 250°C for 2 h; sieved to <0.2 mm; cassava starch binder (4:1); pressed at 89.14 kN/m$^2$ | Combustion efficiency 34.7%, GCV 24.69 MJ/kg, PM reduction 14%, and CO reduction 80% | [54] |
| Rice husk + coconut shell (3:1) (+ tapioca starch binder) | TPM | Rice husk sun-dried and roasted for 10–15 h; sieved to 120 mesh; tapioca starch 6 wt% with 60 mL water; hydraulically pressed with 3-ton force; oven-dried at 55℃ for 24 h | GCV 17.29 MJ/kg, density 0.68 g/cm$^3$, water loss 37.30%, and VM 21.91% | [55] |

| Feedstock | Material Types | Operating Conditions | Performance | Ref. |
|---|---|---|---|---|
| Rice husk + sugarcane bagasse + durian seed flour (binder) | BBM | Carbonized at 300℃ for 1 h; durian seed flour binder 20 wt%; sieved to 60 mesh; oven-dried at 100℃ for 1 h | GCV 21.31 MJ/kg, MC 5.2%, ash 20.76%, VM 43%, and FC 28% | [56] |
| Rice husk + sugarcane bagasse (3:2) (+ tapioca starch binder) | BBM | Open-fire carbonized for 30 min; tapioca starch binder with 17 mL water; sieved to 60 mesh; manually pressed; oven-dried at 100°℃ for 30 min | GCV 28.64 MJ/kg, MC 8.31%, ash 30.41%, VM 37.10%, and FC 32.49% | [57] |
| Rice husk + cow feces (+ tapioca starch, molasses, waste cooking oil binders) | BBM | Husk carbonized for 2 h and feces for 4–5 h; tapioca starch 10%, molasses 8%, and waste cooking oil 2% as binders; manually pressed at 500 g/unit; sun-dried for 7–8 d | GCV 16.19 MJ/kg, burning rate (BR) 0.14–0.24 g/min, and ash 29.4–32.08% | [58] |
| Coconut shell | BBM | 7 d initial sun-dried; drum carbonized 5 h; sieved to 28 mesh; tapioca binder (1:5); manually pressed at 18 kN/$m^2$ for 2 min; 5 d final sun-dried | Density 1199.34 kg/$m^3$, drop test 0%, GCV 27.11 MJ/kg, and S 0.03% | [50] |
| Coconut shell charcoal (+ cassava starch, corn starch binders) | BBM | 14 d air-dried; bucket carbonized for 1 h; sieved to 60 mesh; cassava or corn starch binder 5–15%; manually hammer-pressed; 7 d sun-dried | Density 0.764 g/$cm^3$, MC 2.88–8.13%, ash 1.72–5.85%, FC 70.79%, GCV 31.51 MJ/kg, and boiling time 15.88 min | [59] |
| Coconut shell + corncob (+ tapioca starch binder) | BBM | Coconut shell carbonized at 400–600℃ for 45 min and corncob at 200–400℃ for 120 min; sieved to 80 mesh; tapioca starch binder 5 wt%; hand-pressed at 100 kg/$cm^2$; sun-dried for 3 d; oven-dried at 60–80℃ for 30 min | GCV 24.99–25.83 MJ/kg, MC 2.03–3.14%, ash 9.18–9.84%, VM 27.04–27.41%, and FC 60.57–61.09% | [60] |
| Oil palm shell char (+ tapioca starch binder) | BBM | Palm shell pyrolyzed; char sieved to 20 mesh; tapioca starch binder 4 wt%; compressed at 5,000-ton force | GCV 25.10 MJ/kg, MC 4.45%, ash 5.11%, and VM 40.49% | [61] |
| Oil palm shell (+ LDPE, tapioca starch binders) | BBM | 2 d sun-dried; carbonized at 400℃ for 4.5 h; sieved to 20 and 40 mesh; LDPE 0–10%; tapioca binder 8%; compressed under 60 kg load; oven-dried at 60℃ for 3 h | GCV 27.08–28.76 MJ/kg, MC 8.05–8.94%, ash 6.84–7.61%, VM 11.04–17.20%, BR 0.45–0.64 g/min, and burning time (BT) 62–84 min | [62] |
| Oil palm EFB + coconut shell (+ CPO sludge binder) | TPM | Preheated at 40℃ for 12 h; torrefied at 300℃ for 1 h; char sieved to 100 mesh; CPO sludge binder 20 wt%; compacted into cylindrical pellets | GCV 26.10 MJ/kg, MC 3.15%, ash 5.8%, and VM 9.9% | [63] |
| Oil palm EFB + frond char blend (1:1) (+ tapioca starch binder) | BBM | Carbonized at 150℃ for 3 h; sieved to 30, 50, and 70 mesh; tapioca starch binder 6–10%; manually pressed | MC 0.3–4.1%, ash 43.13–59.2%, density 0.50–0.57 g/$cm^3$, CS 1.12–1.65 MPa, and BR 0.11–0.23 g/min | [64] |
| Oil palm EFB (+ LDPE, tapioca starch binders) | BBM | Initial drying; sieved to 20 and 40 mesh; LDPE 0–10%; tapioca binder 8%; compressed under 60 kg load; | GCV 20.56–21.69 MJ/kg, MC 15.92–16.12%, ash 17.04–18.03%, | [62] |

| Feedstock | Material Types | Operating Conditions | Performance | Ref. |
|---|---|---|---|---|
| | | oven-dried at 60℃ for 3 h; EFB carbonized at 400℃ for 3 h | VM 20.89–24.08%, BR 0.52–0.66 g/min, and BT 46–54 min | |
| Oil palm mesocarp fiber (+ tapioca starch binder) | BBM | Preheated at 105℃ for 12 h; carbonized for 1.5 h; sieved to 60 mesh; tapioca binder (2:1); 200 mL water solvent; sun-dried for 24 h | MC 5.7%, ash 11.28%, BT 77 min, and BR 0.38 g/min | [65] |
| Oil palm mesocarp fiber (+ tapioca starch binder) | BBM | Preheated at 105℃ for 1 h; pyrolyzed at 350℃ for 2 h; sieved to 80 mesh; tapioca binder (2:1); water (1:10); manually compacted; oven-dried at 75℃ for 24 h | MC 3.5%, GCV 27.73 MJ/kg, BR 2.578 g/s, and ignition time (IT) 23.27 s | [66] |
| Oil palm trunk bark + corncob (+ wastepaper pulp binder) | RB | Sun-dried to 9.27% moisture; sieved to <2 mm; wastepaper pulp binder 10 wt%; pressed at <7 MPa; air-dried for 30 d | MC 9.24–10.00%, density 0.38–0.40 g/cm$^3$, water resistance 87.60–92.00%, shatter index 98.28–99.08%, CS 18.47–21.75 MPa, and GCV 16.54–16.91 MJ/kg | [67] |
| Coconut husk charcoal (+ tapioca starch binder) | BBM | High-temperature incomplete carbonized; charcoal powder sieved; tapioca starch binder 5 wt%; screw-extruded; dried to constant weight | GCV 25.70 MJ/kg, MC 7.15%, ash 13.22%, BR 0.1588 g/min, and shatter index 2.49% | [68] |
| Coconut husk charcoal (+ tapioca starch binder) | BBM | High-temperature incomplete carbonized; charcoal powder sieved; tapioca starch binder 15 wt%; screw-extruded; dried to constant weight | GCV 14.21 MJ/kg, MC 11.67%, ash 23.48%, BR 0.1359 g/min, and shatter index 0.56–0.59% | [68] |
| Young coconut coir briquette (+ tapioca starch binder) | RB | Raw material sun-dried; sieved to 10 mesh; tapioca + water binder; pressed at 50 kg/cm$^2$ | MC 24.72–29.72%, ash 2.21%, FC 24.94%, GCV 13.12 MJ/kg, and TGA/DTG mass loss 78% at 45℃ | [69] |
| Coconut fiber briquette (+ tapioca starch binder) | RB | Washed and sun-dried; sieved for uniform particle size; tapioca starch + water binder; hot-pressed at 2 MPa; re-dried after pressing | HHV 19.83 MJ/kg, sample mass 5.35 g, combustion temperature 66.5℃, IT 106 s, and BT 23.88 min | [70] |
| Cocoa pod shell + red fruit pulp (3:7) (+ tapioca starch binder) | BBM | Sun-dried for 3–6 d; pyrolyzed at 500℃ for 4 h; sieved to 50 mesh; tapioca binder 10 wt%; hydraulically pressed at 100 kg/cm$^2$; baked at 105℃ for 6 h | GCV 26.86 MJ/kg, MC 5.63%, ash 9.45%, VM 18.65%, and FC 66.27% | [71] |
| Cocoa shell + dry ketapang leaves (9:1) (+ tapioca starch binder) | BBM | Sun-dried; separately pyrolyzed; sieved to 60 mesh; tapioca binder 10 wt%; pipe-compacted; sun-dried for 7 d | GCV 20.38 MJ/kg, MC 13.01–13.02%, AC 10.31%, VM 33.28%, and BT 76.5 min | [72] |
| Candlenut shell (+ tapioca starch binder) | BBM | Preheated at 105℃ for 1 h; pyrolyzed at 350℃ for 2 h; sieved to 80 mesh; tapioca binder (2:1); water (1:10); compacted in hollow iron mold; oven-dried at 75℃ for 24 h | MC 2.63%, GCV 17.29 MJ/kg, BR 5.85 g/s, and IT 10.25 s | [66] |

| Feedstock | Material Types | Operating Conditions | Performance | Ref. |
|---|---|---|---|---|
| Cashew nutshell charcoal (+ tapioca-ethanol binder) | BBM | 5 h sun-dried; pyrolyzed at 350℃; sieved to 200 mesh; tapioca–ethanol binder 8–12%; hydraulically pressed at 29.4 MPa for 5 min; oven-dried at 50℃ for 4–6 h | GCV 29.49 MJ/kg, MC 5.30%, ash 4.96 wt%, VM 17.16%, FC 72.62%, cooking cost reduction 37%, return of investment (ROI) 23.55%, payback time 3.42 y, and break-even point (BEP) 50.09% | [73] |
| Pinecone charcoal (+ tapioca starch binder) | BBM | Carbonized at 350–450℃ for 4 h; sieved to 100–119 mesh; tapioca binder 15 wt%; pressed at 100 kg/cm$^2$; oven-baked at 70℃ for 6 h | GCV 27.37 MJ/kg, MC 7.79%, ash 9.57%, VM 0.90%, and FC 81.73% | [74] |
| Pinecone charcoal (+ tapioca starch binder) | BBM | Carbonized at 350–450℃ for 4 h; sieved to ≥120 mesh; tapioca binder 15 wt%; pressed at 100 kg/cm$^2$; oven-baked at 70℃ for 6 h | GCV 27.31 MJ/kg, MC 7.65–7.66%, AC 9.80%, VM 0.92%, density 0.605 g/cm$^3$, and BR 0.119 g/s | [74] |
| Scots pinecone (*Pinus sylvestris* L.) briquette | RB | Shredded and sieved to 6 mm; wetted to 20% moisture; binder-free; pressed at 21 MPa; combusted in an 8 kW grate-fired boiler for 6 h | HHV 20.05 MJ/kg, LHV 18.77 MJ/kg, MC 8.49%, ash 0.69 wt%, CO <2000 mg/m$^3$, and NOx <120 mg/m$^3$ | [75] |
| Pine needle char (+ pine resin binder) | BBM | Slow-pyrolyzed at 300℃ for 3 h; sieved to <2 mm; pine resin binder (5:1); pressed at 5.5 MPa; sun-dried for 1 d | GCV 22.19 MJ/kg, density 917.27 kg/m$^3$, MC 5.04%, IT 12.19 s, shatter resistance >99%, and BT 30–45 min | [76] |
| Pine needle leaves + coal (+ starch binder) | BCM | Pine dried and sieved; mixed with coal and starch binder; press-molded | MC 5.56–6.12% and ash 6.70–7.40% | [77] |
| Pine needle leaves + coal (+ sago binder) | BCM | Pine dried and sieved; mixed with coal and sago binder; press-molded | MC 6.12–6.38% and ash 6.25–6.70% | [77] |
| *Pinus* spp. sawdust | RB | Directly densified without carbonization; moisture 7.5–8.7%; binder-free; pressed at 20 MPa and 50℃ for 5 min; conditioned at 20℃ and 50% RH for 7 d | HHV 20.5–22.8 MJ/kg, MC 4.1–7.2%, ash 0.1–1.1%, VM 82.9–90.7%, density 813.9–1014.4 kg/m$^3$, energy density 16.9–21.1 GJ/m$^3$, CS 4.9–40.8 N/mm, and impact resistance 46.7–200% | [78] |
| Norway spruce cone briquette (*Picea abies*) | RB | Shredded and sieved to 6 mm; wetted to 20% moisture; binder-free; pressed at 21 MPa; combusted in an 8 kW grate-fired boiler for 6 h. | HHV 20.75 MJ/kg, LHV 19.52 MJ/kg, MC 9.06%, ash 1.29 wt%, CO <2000 mg/m$^3$, and NOx <140 mg/m$^3$ | [75] |
| European larch cone briquette (*Larix decidua*) | RB | Shredded and sieved to 6 mm; wetted to 20% moisture; binder-free; pressed at 21 MPa; combusted in an 8 kW grate-fired boiler for 6 h | HHV 20.83 MJ/kg, LHV 19.58 MJ/kg, MC 8.78%, ash 1.15 wt%, CO 3500–3890 mg/m$^3$, and NOx 188.20 mg/m$^3$ | [75] |

| Feedstock | Material Types | Operating Conditions | Performance | Ref. |
|---|---|---|---|---|
| *Cupressus lusitanica* char (+ cow dung binder) | BBM | Shade-dried for 14 d; carbonized in an oxygen-deficient kiln for 1–1.5 h; sieved to 0.6 mm; cow dung binder (3:1) + water; manually pressed; sun-dried to 12–15% moisture | GCV 28.25 MJ/kg, MC 4.29%, VM 22.12%, FC 68.94%, ash 5.53%, and S 0.02% | [79] |

As summarized in Table 2, FAS feedstocks exhibit substantial variation in briquette performance because both material characteristics and processing conditions influence the final properties. Carbonized or biochar-based materials generally show increased fixed-carbon concentration and reduced volatile matter relative to raw biomass, although calorific value and combustion behavior remain dependent on feedstock composition, thermal severity, binder formulation, and densification conditions. Blending, particle-size adjustment, binder selection, and compaction can further modify density, mechanical. Overall, the evidence indicates that FAS bio-briquette performance is determined by the interaction of feedstock properties, pretreatment, and subsequent processing rather than by feedstock type alone. The mechanical and handling performance reported in Table 2 is also expressed using different durability-related metrics, which evaluate distinct modes of briquette failure rather than representing equivalent measures of mechanical quality. To clarify these distinctions, Table 3 summarizes the definitions, relevant standards, and principal factors affecting compression strength, shatter resistance, impact resistance, water resistance, and abrasion resistance.

**Table 3.** Key durability parameters and their distinct measurement characteristics.

| | Compressive Strength | Shatter Resistance | Impact Resistance | Water Resistance | Abrasion Resistance |
|---|---|---|---|---|---|
| Definition | Maximum compressive load during handling and storage [80] | Reflects resistance to breakage and fines during handling [81] | Evaluates resistance to damage from dropping [80] | Measured through laboratory water immersion tests [80] | Assesses resistance to abrasion during handling and transport [80] |
| International Standard | ASTM E9-09 [82] | ASTM D440-86 [83] | ASTM D440-07 [82] | ASTM D779-03 [84] | ISO 17831-2:2015 [82] |
| Factor Affecting | Homogeneity, particle size, density [82] | Particle size and binder properties [85] | Pressure, temperature, particle size [86] | Material type, pressure, and particle size [87] | Testing time and rotational speed [80] |

These parameters should therefore be interpreted according to the specific failure mechanism and test method being evaluated. Accordingly, compression strength, shatter resistance, impact resistance, water resistance, and abrasion resistance are complementary indicators and should not be treated as interchangeable measures of briquette durability.

### 2.4. Application and utilization spectrum of bio-briquettes

#### 2.4.1. Domestic and small-scale energy source

FAS bio-briquettes are primarily suitable for domestic cooking, household heating, and other small-scale thermal applications because densification converts loose residues into compact fuels with higher bulk density, more uniform combustion, and easier handling. Their performance is mainly governed by calorific value, VM, MC, density, and ash content [88]. Softwood-derived briquettes generally exhibit easier ignition and faster combustion because of their higher VM, resulting in shorter combustion duration and moderate energy density [89]. In contrast, bio-briquette from fibrous agricultural residues typically contain higher FC and lower VM, favoring higher energy density and prolonged combustion but requiring higher ignition temperatures [90]. Increasing carbonization can further enhance energy density and combustion duration, although excessive severity may impair ignitability through further VM loss. In both feedstocks, excessive binder or ash can reduce the effective combustible fraction. The reviewed studies therefore suggest that moderate carbonization and sufficient densification are more practical for household applications than maximizing calorific value alone. The resulting trade-off can be managed through feedstock blending, controlled

carbonization, and binder optimization to balance ignition, combustion duration, and structural integrity [91]. Similarly, the environmental advantage of FAS briquettes should not be assumed solely from their biomass origin, since MC, ash, combustion conditions, and stove configuration strongly influence emissions. Their greatest domestic potential consequently lies in formulations that provide a balanced combustion profile while converting locally available residues into convenient and durable fuel [92].

#### 2.4.2. Co-firing fuel in coal-fired power plants

At a larger scale, FAS bio-briquettes can serve as supplementary fuels in coal-fired power plants to partially displace fossil fuel while utilizing existing thermal-generation infrastructure. Densification improves the handling and feeding of FAS residues, while their biogenic carbon fraction can reduce the fossil-carbon contribution of electricity generation. The effectiveness of co-firing is mainly influenced by calorific value, MC, ash composition, particle size, and briquette durability, because these properties determine fuel feeding, combustion behavior, and ash-related problems. The principal trade-off is that increasing the biomass fraction may increase renewable-fuel utilization but can simultaneously lower energy density and intensify slagging, fouling, or corrosion when K, Ca, and Si are present at high levels. Ash-related problems can be mitigated through suitable additives; for example, 1–6 wt% magnesium oxide (MgO), 1 wt% $Al_2O_3$, and 1–3 wt% dicalcium phosphate ($CaHPO_4$) reduced ash deposition and increased ash melting temperature during biomass–coal co-firing [93].

For instance, palm shell charcoal–low-rank coal briquettes achieved a calorific value of 6438 cal/g, with the resulting fuel quality strongly dependent on the raw-material composition and binder type [94]. Accordingly, the optimum co-firing condition should be determined from boiler compatibility rather than biomass substitution rate alone. Moderate biomass substitution is generally more realistic for conventional coal-fired units; for example, India has mandated 5–10% biomass co-firing in thermal power plants, with an estimated reduction of 38 million tons of carbon dioxide ($CO_2$) emissions annually. At 7% co-firing, approximately 0.25–0.3 million tons of biomass pellets are required per GW of capacity, illustrating the substantial feedstock and infrastructure requirements at large scale [95]. Feedstock blending, torrefaction/carbonization, particle-size control, and appropriate fuel preparation can be used to improve fuel quality and mitigate operational limitations [96]. Thus, FAS bio-briquettes are better viewed as a supplementary coal-displacement fuel rather than a direct coal replacement, with their practical contribution ultimately determined by the balance among emission reduction, fuel quality, feedstock availability, and boiler performance.

#### 2.4.3. Reducing agent in metallurgical applications

High-carbon FAS bio-briquettes can function as renewable reducing agents in metallurgical processes, where their carbon reacts with oxygen-bearing metal oxides such as iron (Fe), chromium oxides ($Cr_2O_3$), plumbum (Pb), and zinc (Zn) facilitating metal reduction and recovery in ironmaking, steelmaking, and ferroalloy production. In a recent study, the reduction of metallurgical dust proceeded through five stages, with apparent activation energies of 109.83 kJ/mol for stages five [97]. Similarly, briquetting chrome ore ($FeCr_2O_4$) dust with carbonaceous reducers has been demonstrated as a means of recovering fine feedstock and improving material utilization in ferrochrome (FeCr) production, although reducer ash content strongly affects thermal stability and electrical conductivity, with lower ash associated with better smelting performance [98].

The suitability of FAS briquettes as reductants is therefore governed by FC, reactivity, ash and sulfur content, porosity, and mechanical strength rather than carbon content alone. Carbonization can increase FC and develop a porous structure that enhances reaction kinetics, while the typically low sulfur content of biomass-derived carbon can reduce sulfur input compared with fossil-derived reductants. However, excessive carbonization may reduce reactive components, whereas highly porous structures can improve reactivity at the expense of mechanical durability, while excessive ash can impair smelting behavior and dilute the effective carbon fraction [99]. This trade-off makes partial substitution of coke or other fossil reductants more realistic than complete replacement, particularly because biomass is most effective for metallurgical applications when used in compressed or preliminary carbonized forms [100]. Controlled carbonization and feedstock blending may therefore help balance carbon content and reductive reactivity while maintaining the quality required for metallurgical operation. Accordingly, the most promising FAS briquettes are not necessarily those with the highest FC, but those providing sufficient reductive reactivity while maintaining suitable ash and sulfur contents and adequate mechanical integrity.

#### 2.4.4. Additive or filler in eco-friendly construction materials

Once FAS bio-briquettes are used for energy, their remaining ash and carbonaceous residues do not necessarily represent the end of their value chain. These residues can be redirected into bricks, blocks, cement composites, and other construction materials where their fine particles can act as fillers that modify density, pore

structure, and thermal behavior. This creates an interesting utilization pathway because a material originally designed to release energy is subsequently converted into a component of a construction product. For example, cellular lightweight bricks produced from bio-briquette ash were 43% lighter, 13% stronger, and exhibited 66% lower thermal conductivity than conventional fly-ash bricks, while model-room application achieved 6% better indoor temperature control and 29% cost savings, supporting their use in non-load-bearing walls [101]. Previous study also shown that biomass ash serve as supplementary cementitious materials and aggregates [102].

The performance of bio-briquette residues in construction materials is strongly governed by waste type, replacement level, and processing conditions. Across waste-incorporated bricks, CS 3–100 MPa, bulk density 1200–2500 kg/m$^3$, water absorption 5–35%, and thermal conductivity 0.19–1.02 W/m.K [103]. Bio-based wastes generally promote higher porosity and better thermal insulation through biomass burnout and pore formation, but this advantage may come with lower mechanical performance and higher water absorption than industrial-waste-based systems. Thus, maximizing residue incorporation is not necessarily desirable; partial and application-specific incorporation is more appropriate, particularly where lightweight and thermal insulation are prioritized over maximum strength. For FAS residues, their suitability should therefore be assessed based on the balance between density, thermal performance, water resistance, and mechanical requirements rather than residue utilization alone.

## 2.5. Challenges, limitations, and future research prospects

### 2.5.1. Scale-up challenges

The major challenge in scaling up FAS bio-briquetting is maintaining consistent briquette performance when feedstock variability and process fluctuations become more pronounced. Variations in particle size, MC, chemical composition, and bulk density can shift the balance between density, mechanical strength, and combustion behavior, making results obtained under controlled laboratory conditions difficult to reproduce at larger scales [104]. This limitation becomes more critical for FAS residues because low bulk density and hygroscopicity introduce additional losses during storage, handling, and transportation, as they are less stable and more prone to spillage or loss during movement and processing [105]. The critical scale-up issue is not simply transferring laboratory operating conditions to larger equipment but maintaining process stability despite variable feedstock and changing operating conditions. Future research should therefore shift from identifying a single optimum formulation toward robust process windows, supported by feedstock classification, strategic blending, adaptive physicochemical control, and continuous monitoring. Performance should also be validated across different feedstock batches and production scales to determine whether laboratory-developed briquettes can retain their structural and combustion characteristics under realistic industrial conditions.

### 2.5.2. Economic, market, and logistical constraints

The economic viability of FAS bio-briquettes is strongly governed by the spatial relationship between biomass supply, production capacity, and end-use demand. Although centralized production can benefit from economies of scale and more efficient processing, transporting low-density FAS residues over long distances can rapidly increase logistics costs before densification. Conversely, decentralized production reduces feedstock transport distances but may sacrifice economies of scale and process efficiency. This creates a fundamental trade-off in which larger production capacity does not necessarily translate into lower overall cost s [2]. The economic competitiveness of FAS briquettes depends strongly on production cost and market conditions, particularly labor, capital, and operating costs. A small-scale assessment of agricultural-residue briquetting reported that labor accounted for approximately 30% of total expenses, while gasoil contributed 10–16%. Economic performance also varied substantially among feedstocks, with net present value (NPV) of €66,526, €67,189, −€34,317, and −€44,932 for rattan waste, coconut shells, sugarcane bagasse, and banana peels, respectively. These results indicate that the economic feasibility of briquetting is highly feedstock-dependent and sensitive to briquette market price, discount rate, and capital cost, suggesting that the availability of low-cost residues alone does not guarantee commercial viability [106]. Accordingly, FAS briquetting should be evaluated through location- and feedstock-specific techno-economic assessment (TEA) which integrating feedstock cost, transport distance, production scale, and local market demand rather than production cost alone. Neither centralized nor decentralized production is universally optimal, as their economic advantage depends on local supply-chain and market conditions.

### 2.5.3. Environmental and policy considerations

The environmental advantage of FAS bio-briquettes should not be attributed solely to their biogenic origin, as the overall benefit depends on feedstock sourcing, processing energy, transportation, combustion conditions, and emission control. Although replacing fossil fuels can reduce fossil-carbon inputs and provide an alternative

pathway for agricultural residues that might otherwise be openly burned, high ash content and feedstock-specific inorganic constituents can introduce additional emission and ash-management concerns. This highlights the need to evaluate FAS briquettes through life-cycle and application-specific environmental assessment rather than assuming inherent carbon neutrality. From a regulatory perspective, broader adoption is also constrained by the need for consistent fuel specifications and emission requirements. Internationally, ISO 17225-7:2021 provides fuel quality classes and specifications for non-woody briquettes, including herbaceous, fruit, aquatic biomass, and biomass blends, while ISO 17225-3:2021 covers wood briquettes [47]. For FAS materials that fall outside these specific categories or involve thermally treated feedstocks, appropriate classification and additional characterization may therefore be necessary. The key policy challenge is consequently not simply promoting biomass utilization, but establishing consistent quality, emission, and sustainability criteria that allow FAS briquettes to demonstrate environmental benefits without compromising combustion or environmental performance.

#### 2.5.4. Future research directions and integrated optimization

Future research should increasingly explore engineered FAS bio-briquettes rather than relying solely on conventional densification. Emerging approaches include nano-binders, catalytic additives, and hybrid formulations with mineral or secondary materials, which may improve bonding, combustion behavior, or selected fuel properties; however, these benefits must be weighed against additional material cost, processing complexity, ash modification, and potential environmental burdens. The more important frontier is therefore not simply achieving higher strength or calorific value, but tailoring briquette properties to specific applications while maintaining process simplicity and scalability. In parallel, machine learning and real-time monitoring could enable predictive control of moisture, particle characteristics, pressure, and temperature under variable feedstock conditions, although their reliability remains dependent on the quality and diversity of available datasets. Importantly, these technological developments should be evaluated together with TEA and life cycle assessment (LCA), since an additive or advanced process that improves laboratory-scale performance may become less attractive when additional energy, materials, capital, or environmental impacts are considered. Future studies should consequently prioritize integrated optimization of material formulation, process control, economic feasibility, and life-cycle performance rather than pursuing individual property improvements in isolation.

## 3. Conclusion

The critical synthesis of FAS bio-briquette research shows that briquette performance is governed by the coupled effects of feedstock characteristics, chemical composition, pretreatment, and densification conditions rather than by the briquetting technology alone. Piston, screw, and roller presses provide different advantages depending on feedstock morphology, particle characteristics, and production requirements, while drying, size reduction, torrefaction, steam explosion, and carbonization can substantially modify moisture behavior, compressibility, energy characteristics, and bonding during densification. At the material level, lignin predominantly contributes to inter-particle cohesion and durability, cellulose supports structural integrity and fuel formation, and the greater thermal reactivity of hemicellulose promotes volatile release and ignition; meanwhile, ash-forming minerals such as K, Na, Ca, Mg, and Si strongly influence ash behavior and may increase the risks of slagging and fouling. These interactions explain the broad variation in density, calorific value, MC, ash contents, VM, FC, mechanical strength, and combustion characteristics reported across FAS-derived briquettes, and demonstrate that improvements in one performance attribute may occur at the expense of another. Accordingly, MC, particle size, compaction pressure, temperature, and dwell time cannot be defined by universal operating conditions but should be optimized according to feedstock-specific properties and intended applications. The principal remaining challenge is therefore to convert inherently heterogeneous agricultural and softwood residues into reproducible briquettes while maintaining technical performance during scale-up and controlling production, storage, transportation, and environmental burdens. Application requirements further complicate this optimization because domestic energy use, coal co-firing, metallurgical reduction, and construction-material utilization impose different requirements. Future progress should consequently emphasize robust feedstock classification and blending, application-specific process optimization, predictive modelling and process monitoring, and larger-scale validation, supported by TEA and LCA and appropriate quality standards to establish whether improvements in briquette performance can be translated into technically consistent, economically feasible, and environmentally sustainable FAS bio-briquette systems.

## Author contributions

**Mizanurafi' Ghifarhadi Prasiefa**: Conceptualization, Project Administration, Supervision, Validation, Writing – Review & Editing; **Moh. Fatur Rizki**: Data Curation, Formal

Analysis, Validation; **Evi Nadilah Giandita**: Methodology, Writing – Review & Editing, Visualization; **Daniyal Firmansyah**: Visualization, Project Administration; **Ahmad Daily Yahya**: Resources, Writing – Original Draft; **Azka Azzam Mubarok**: Writing – Original Draft.

## Conflicts of interest

The authors declare that they have no known competing personal relationships that influence the work reported in this paper.

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