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Calorific value performance of sago dregs biomass products for coal co-firing material

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ABSTRACT

Fossil fuels (petroleum, natural gas, and coal) generate significant CO_2, SO_x, and NO_x emissions, leading to environmental concerns. Co-firing biomass with coal is a potential mitigation strategy, but raw biomass faces challenges such as high moisture and ash content and low calorific value. The pyrolysis process can enhance biomass quality into biochar, which has lower moisture and higher fixed carbon, increasing energy value. However, biochar still lacks the energy density and calorific value of coal. To address this, a hybrid bio-coke was developed by combining biochar and bio-oil from pyrolysis, resulting in a solid fuel with coal-like properties. This study utilized sago waste from Southeast Sulawesi, producing pellets (SD), biochar (BC), and hybrid biocoke (HBC), which were blended with sub-bituminous coal from Central Kalimantan in various ratios. As the coal fraction increased, performance improved. Due to high moisture and ash, SDC products had low calorific values of 4.155 to 5.466 cal/g. BCC showed a calorific value of 5.898 to 6.810 cal/g with over 55 wt% fixed carbon but suffered from low bulk density. HBCC demonstrated the best performance, with calorific values of 6.945 to 7.108 cal/g, moisture between 4% and 9%, and fixed carbon levels of 54% to 68%. The optimal formulation was a 1:1 ratio (HBCC-4), yielding 6.930 cal/g with a fixed carbon content of 60.90 % and a 1.819 g/cm³ density. This combination enhances energy efficiency and thermal stability, comparable to sub-bituminous coal. Upgrading SD to HBC, before or after blending with coal, significantly enhances energy quality. Sago dregs-based HBC has the potential to be a competitive coal substitute, supporting a sustainable energy transition, while reducing dependence on fossil fuels.

Keywords: co-firing, sago dregs, biochar, hybrid biocoke, coal, renewable energy.

INTRODUCTIONS

Energy is a fundamental component of global development, vital to economic growth, industrialization, and people's quality of life. Data from the International Energy Agency, (2024) shows that more than 60% of the world's primary energy still relies on fossil fuels, primarily coal. Coal continues to be the primary energy source, accounting for over 36% of global electricity generation. Relying on coal is crucial for heavy industries, especially steel and metal smelting. However, it has two main drawbacks: potential supply constraints and increased emissions. The combustion process of fossil fuels contributes approximately 74% of CO_2 emissions, as well as 26% of SO_x and NO_x, which contribute to climate change, acid rain, and global air quality degradation (Chen et al., 2021; Wang et al., 2025). Therefore, to achieve the carbon-neutral target and sustainable development goals (SDGs), various countries, including Indonesia, have begun to adopt co-firing strategies as an effective mitigation to reduce carbon emissions from coal combustion (Knapp et al., 2019; Zhai et al., 2025).

Co-firing is a co-combustion system that combines biomass with coal. This combination can change the composition of flue gases and reduce carbon emissions, because biomass is considered a carbon-neutral source with relatively balanced growth and combustion, thus reducing the CO_2 emission footprint (Liu et al., 2023;

Ibitoye et al., 2023). However, the use of biomass in its raw form has technical limitations, such as low energy density, high moisture content, and high volatility, resulting in lower combustion efficiency, which can cause slagging, fouling, corrosion, and abrasiveness in the combustion system and increase equipment maintenance costs (Chen et al., 2021; Ghazidin et al., 2023; Zhang et al., 2021). Raw biomass has a calorific value ranging from 8–15 MJ/kg, much higher than coal, which generally reaches 20–30 MJ/kg (Jahiding et al., 2021), so a larger volume of biomass is required to produce equivalent energy, this has a direct impact on increasing logistics, transportation and storage space costs at industrial sites, because of these limitations, a concept for developing solid fuels derived from biomass is needed to have thermal characteristics closer to coal before being applied in a co-firing system.

Indonesia possesses significant potential for biomass derived from various agro-industrial waste products. One underutilized resource is sago dregs, a byproduct of the sago industry primarily found in Papua, Maluku, and Sulawesi. The country produces approximately 5.2 million tons of sago annually, with about 60% comprising sago dregs. Unfortunately, much of this pulp lacks economic value (Rambli et al., 2019). Sago dregs contain high levels of lignocellulose: 38% cellulose, 27% hemicellulose, 23% lignin, and an ash content (Susanto et al., 2024). This composition suggests that sago dregs could serve as an alternative fuel source. However, the difference in characteristics is a limiting factor, namely the high moisture content reaching 50–60% with a calorific value of 3.500 cal/g, far below the coal standard, which ranges 5.000–6.500 cal/g (Jahiding et al., 2024; Rambli et al., 2018; Siruru et al., 2022). Therefore, sago dreg requires improving energy quality through thermal conversion technology before it can be widely used in co-firing systems.

Pyrolysis is an effective method for improving the quality of biomass, resulting in three main products: solids (biochar), liquids (bio-oil), and gases (Bridgwater, 2012; Ungureanu et al., 2025). Biochar, a significant byproduct of biomass pyrolysis, has been extensively researched to overcome the limitations of raw biomass. Compared to the original biomass, biochar features lower water content, higher fixed carbon content, and improved thermal stability. However, it does have some limitations, particularly regarding its calorific value, which ranges moderately from 15 to 20 MJ/kg, and its relatively low energy density (Awad et al., 2024; Siruru et al., 2022; Vilas-Boas et al., 2023). The challenges associated with biochar complicate transportation and storage, potentially leading to instability when used in high proportions within co-firing systems (Wang et al., 2025). As a result, while biochar mitigates some of the limitations of raw biomass, its overall performance still does not compare favorably to coal's.

As a solution to these limitations, one promising innovation is the development of hybrid bio-coke, which combines bio-char and bio-oil in liquid-solid form through injection or blending methods, resulting in a solid fuel with superior characteristics. Research by Jahiding et al. (2021) shows that hybrid bio-coke can produce a calorific value of up to 25 MJ/kg, approaching that of sub-bituminous coal, and has better mechanical durability and thermal stability than conventional biocoke. This advantage is related to the characteristics of bio-char, which is rich in fixed carbon, with bio-oil containing hydrocarbons and combustible fractions, thereby increasing density, calorific value, and combustion quality.

Most research on co-firing has concentrated on mixing coal with raw biomass or biochar. Previous studies have indicated that blending coal with raw biomass can help reduce emissions of CO_2, SO_x, and NO_x. However, this method also encounters technical challenges, such as high ash content and moisture levels, which can cause slagging and fouling in the combustion system (Zhu et al., 2017; Liu et al., 2023). Meanwhile, other studies report that the addition of biochar to the biocoke production process significantly affects the calorific value, compressive strength, fluidity, dilatation, and strength of the coke after the reaction, where increasing the weight fraction of biochar tends to reduce the resulting mechanical and thermal performance (Yustanti et al., 2021; Rejdak et al., 2024). Despite extensive research, raw biomass and biochar still have fundamental limitations, necessitating alternative solid fuels with performance more similar to coal. Studies on blending coal with hybrid bio-coke (HBC) are still very limited, even though theoretically, HBC has greater potential to approach the characteristics of coal. HBC is believed to be able to overcome the weaknesses of raw biomass (high moisture content, low calorific value) while compensating for the limitations of biochar (low energy density). Therefore, the main objective of this study is to analyze the characteristics of coal blends with three sago waste-based biomass products: biomass pellets, biochar, and hybrid bio-coke, as well as evaluate hybrid bio-coke as a more competitive coal substitute fuel compared to raw biomass or biochar.

MATERIAL AND METHODS

Biomass valorizations process

The main raw material used in this study is sago dregs (Figure 1a), obtained from the waste of the sago processing industry in southeast Sulawesi, Indonesia. In the initial stage, the sago dregs are dried in the sun for ± 24 hours to reduce the water content. Then it is ground using a crusher and filtered using a 100-mesh sieve (≈0.25 mm). The sago dregs are then processed into three types of solid fuels, representing stages of gradual improvement in energy quality: raw biomass, carbonized, and hybridized. These are sago dregs pellets (SD), biochar (BC), and HBC.

The sago dregs pelletization (SD) process involves compressing dried and sifted sago dregs powder into cylindrical pellets measuring 2 cm in diameter and 8 cm in height. This compression is performed using a hydraulic press at a pressure of 20 MPa and a temperature of 50 °C for a duration of 5 minutes, resulting in high-density pellets. To produce BC, the converted sago dregs undergo pyrolysis in a heat-resistant steel-lined cylindrical reactor, which is 15 cm in diameter and 45 cm in height, with an effective capacity of 7.95 dm^3. The reactor is heated indirectly using an electric heater, equipped with a digital temperature controller and a condenser to accommodate the liquid fraction. The pyrolysis process runs at 600 °C for 2–4 hours under oxygen-limited conditions, producing two main fractions: solid (biochar) and liquid (bio-oil). The obtained biochar was fixed under inert conditions, sieved again using a 100-mesh sieve to achieve a uniform particle size, and compacted with a pressure of 20 MPa at a temperature of 50 °C for 5 minutes before being characterized.

The next stage, improving the quality of the material into HBC, involves utilizing some of the liquid fraction from pyrolysis (bio-oil) as a natural binder and an additional carbon source to strengthen the biochar structure. The formulation refers to the research of Jahiding et al. (2025), namely mixing biochar from pyrolysis at 600 °C with 20% bio-oil (v/w) through the liquid solid mixing method, the mixture is then homogenized and compacted using a pressure of 20 MPa at a temperature of 50 °C for 5 minutes, producing a high-density hybrid biocoke with strong and stable carbon bonds. Compaction on the three biomass products was carried

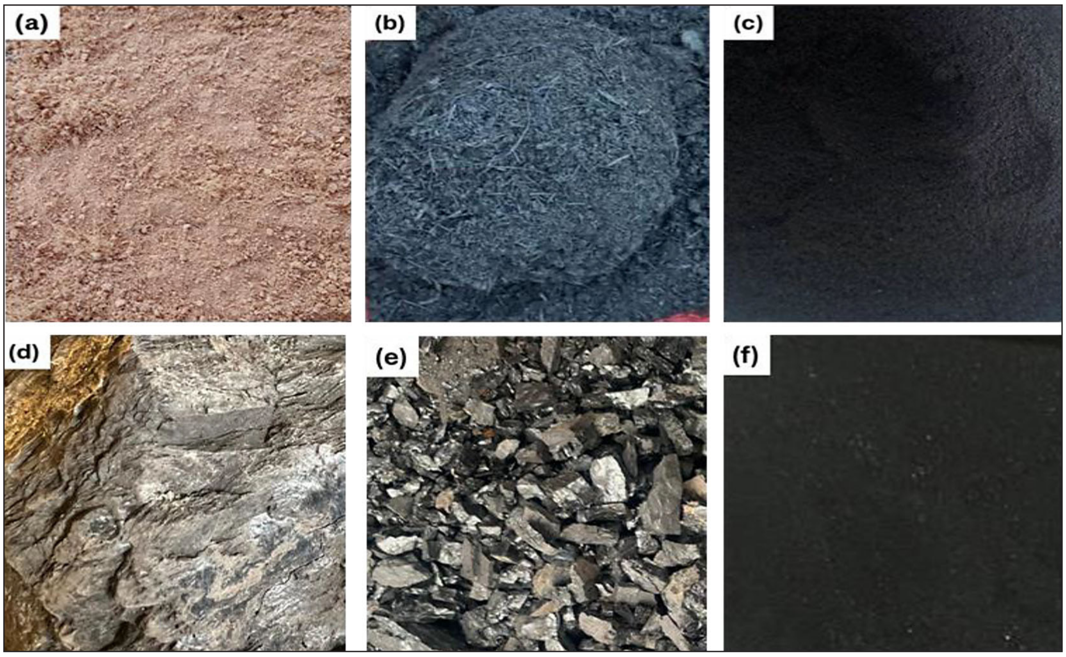

Figure 1. Research raw materials: (a) sago dregs, (b) bio-char, (c) 100 mesh bio-char, (d) bituminous coal, (e) crushed coal, and (f) 100 mesh coal

out only on samples used for initial characterization (SD, BC, HBC) to emit the influence of the carbonization and hybridization processes on the basic characteristics of the fuel including proximate and ultimate content, calorific value and density of the sample before blending with coal, so that the specific contribution of each fuel can be determined.

Biomass-coal blending procedure

The biomass-coal blending procedure in this study was designed to assess the effect of variations in biomass composition on the physicochemical characteristics and energy performance of the blended solid fuel. The coal used was subbituminous coal from Central Kalimantan, Indonesia (Figure 1d). This type was chosen because it is commonly used in the industrial sector, has a relatively high air and volatile matter content, and a medium calorific value. Before the blending process, the coal was prepared by shredding and then drying at 105 °C for 12 hours to reduce the moisture content. It was then ground using a crusher and sieved using a 100-mesh sieve to obtain a fine powder. This preparation ensures the homogeneity and stability of the coal's physical properties during the blending process.

The three previously prepared biomass-based materials, SD, BC, and HBC, were also prepared in powder form to ensure homogeneous mixing with coal. Then, each biomass product was blended with coal in seven variations of mass ratios: 10:0, 9:1, 7:3, 1:1, 3:7, 1:9, and 0:10 (Table 2). These variations produced three series of solid fuels: SDC (Sago dregs-coal), BCC (Biochar-coal), and HBCC (Hybrid biocoke-coal). These fuels went through stages of increasing energy quality, progressing from raw biomass to high-calorie materials (hybrid). Explanations of abbreviations and composition formulation designs are presented in Table 1.

The mixing process was carried out manually using a stainless-steel container and a metal spatula to prevent contamination and ensure homogeneity both visually and texturally. Each ingredient was weighed with an analytical balance with a precision of ± 0.01 g, then stirred slowly for ± 10 minutes until a uniform mixture was obtained. The entire procedure was carried out in dry conditions at a room temperature of 27 °C to prevent moisture reabsorption. After the blending process, the biomass-coal mixture sample was molded into cylindrical biocoke using a hydraulic press with a pressure of 20 MPa at a temperature of 50 °C for 5 minutes. The next stage was a heat treatment at a temperature of ± 150 °C for 1 hour to improve the carbon structure, evaporate residual volatiles, and increase compressive strength, followed by rapid cooling (quenching) with air spraying for ± 5 seconds. This procedure was adapted from research showing that quenching can strengthen the carbon structure while reducing the brittleness of bio-coke briquettes (Yustanti et al., 2021). This method systematically evaluates the performance of coal blending using raw sago dregs-coal (SDC), biochar-coal (BCC), and hybrid biocoke-coal (HBCC), offering an empirical comparison of each product's contribution to enhancing the quality of solid fuels.

Physicochemical characterization

Physicochemical analysis was conducted to determine the quality and energy potential of each sample, including biomass products (SD, BC, and HBC) and blends of biomass products with coal (SDC, BCC, and HBC). All tests were conducted according to ASTM standards to ensure the accuracy, stability, and validity of the results, allowing the data to be used as a basis for implementing solid fuels in industrial co-firing systems. This analysis included chemical analysis (proximate, ultimate, and calorific value) and physical testing (bulk density) to gain a comprehensive understanding of the fuel's energy characteristics and thermal stability.

Table 1. Experimental design of biomass–coal blending compositions (SDC, BCC, HBCC)

Sample	Ratio						
	10:0	9:1	7:3	1:1	3:7	1:9	0:10
SDC	SDC-1	SDC-2	SDC-3	SDC-4	SDC-5	SDC-6	SDC-7
BCC	BCC-1	BCC-2	BCC-3	BCC-4	BCC-5	BCC-6	BCC-7
HBCC	HBCC-1	HBCC-2	HBCC-3	HBCC-4	HBCC-5	HBCC-6	HBCC-7

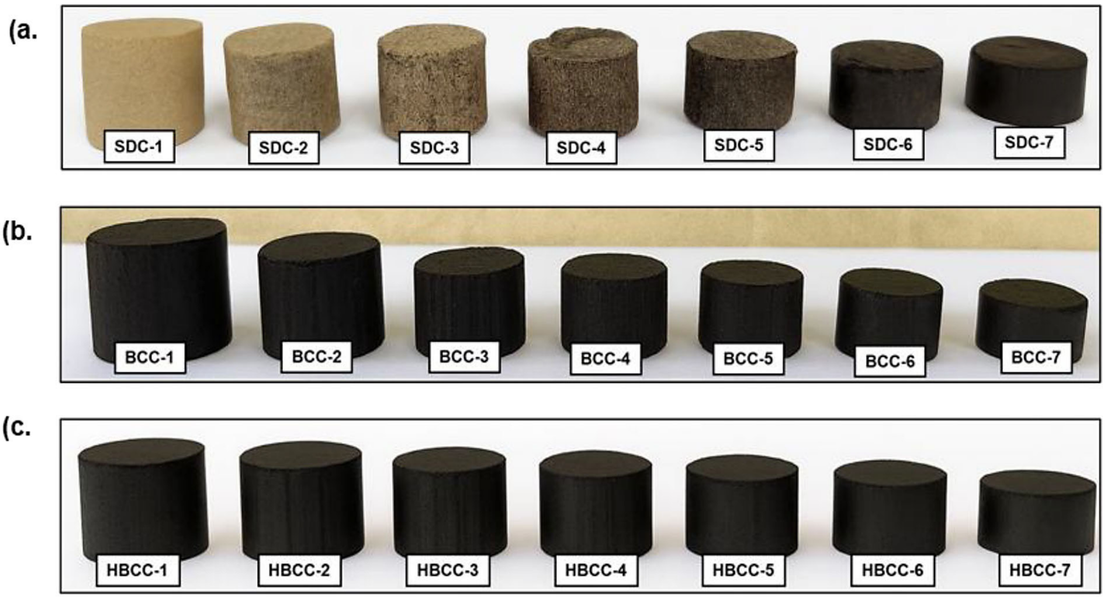

Figure 2. Physical characteristics of biomass–coal blending samples: (a) sago dregs–coal (SDC-1 to SDC-7), (b) biochar–coal (BCC-1 to BCC-7), (c) hybrid biocoke–coal (HBCC-1 to HBCC-7). The sample code variations indicate different blending ratios from 100% biomass (10:0) to 100% coal (0:10)

Proximate analysis was conducted according to ASTM D3172-98 to determine moisture content (M), ash content (Ash), volatile matter (VM), and fixed carbon (FC). Moisture content was measured by drying the samples at 105 °C for 3 hours, while ash content was determined by combustion at 550°C for 3 hours in a muffle furnace. The volatile matter content was determined by heating the sample at 950 °C for 7 minutes under inert conditions, while the fixed carbon was calculated based on the difference of the three parameters. The final analysis refers to the ASTM D5373 standard using a CHN Analyzer to determine the content of carbon (C), hydrogen (H), and nitrogen (N). Oxygen (O) was obtained through a difference calculation, while sulfur (S) was determined using a combustion and titration method, as per ASTM D2492. The calorific value was measured using a bomb calorimeter based on the ASTM D5865 standard. This test is used to determine the calorific value, which serves as the main indicator of the energy potential of solid fuels. While the bulk density was measured at the final stage to assess the structural density and energy efficiency of a unit volume, the measurement was carried out by weighing the mass and test volume of each sample (SD, BC, and HBC) as well as the blended samples (SDC, BCC, and HBCC).

RESULTS AND DISCUSSION

Characteristics of biomass products (SD, BC, and HBC)

The performance of biomass as a solid fuel, whether in the form of SD, BC, or HBC, is greatly influenced by its physicochemical properties that determine combustion stability, energy efficiency, and emission potential (Bridgwater, 2012; Nhuchhen and Afzal, 2017). Raw SD biomass generally has a high air content, excessive volatile content, and significant ash content, which leads to energy waste from evaporation and reduces flame stability. This condition increases the potential for ash deposition, slagging, and fouling due to the accumulation of alkali minerals such as K, Na, and Ca, which can reduce thermal efficiency and accelerate the degradation of combustion equipment. In general, the quality of solid fuel is determined by the proximate parameters of ASTM D3172-98, ultimate ASTM D5373, and calorific value ASTM D5865. These parameters directly influence the combustion initiation process, flame stability, devolatilization rate, and emission intensity. Meanwhile, the density bulk ASTM D7481-18 are evaluated at the final stage to determine the structural density and energy efficiency per unit volume (Abioye et al., 2024; Chen et al., 2021).

Biomass conversion through pyrolysis has been shown to improve various parameters significantly. During the pyrolysis process, reactions such as dehydration, decarboxylation, and devolatilization release water (H_2O), carbon dioxide (CO_2), and volatile compounds. Leads to the formation of a carbon-rich residue with a more condensed aromatic structure (Chen et al., 2021; Uzun et al., 2017). This structural change drastically reduces air and volatile content while increasing the fixed carbon fraction, making the resulting biochar more stable during combustion, more energy efficient, and more compatible with co-firing systems than raw biomass (Han et al., 2017). However, biochar still has the disadvantage of low bulk density. To resolve this issue, a HBC was created by mixing bio-oil with the biochar structure. Bio-oil, which is abundant in medium-chain hydrocarbons (C_5–C_{20}), helps fill the biochar's pores and enhances the connections between particles. This process not only increases the density and energy content per unit volume but also enhances the energy content due to the properties of bio-oil, which resemble liquid fuel fractions (Jahiding et al., 2025; Yustanti et al., 2021).

Table 2 shows that raw biomass (SD) has a very high moisture content of 17.75 wt%, far exceeding the ideal limit of ≤10 wt%. This condition explains the low energy efficiency of SD because most of the heat is lost during the evaporation process. After pyrolysis, the moisture content decreases drastically to 3.70 wt% in BC and 4.13 wt% in HBC, indicating that the energy previously lost due to moisture can be converted into increased thermal efficiency and calorific value (Khater et al., 2024; Rambli et al., 2019). A similar pattern is seen in the ash content, which was initially very high at 29.96 wt% in SD, but significantly reduced to 5.57 wt% in BC and 7.53 wt% in HBC. This decrease directly impacts the potential for slagging and fouling, which contribute to scale formation in the combustion system (Egbosiuba et al. 2022; Rambli et al. 2018).

Furthermore, the volatile matter content showed a significant decrease, dropping from 30.04 wt% in the SD sample to 9.59 wt% in the BC sample and 12.58 wt% in the HBC sample. This reduction in volatile matter demonstrates the effectiveness of the devolatilization process, during which thermal organic compounds such as alcohol, acids, and tar evaporate, leaving behind a solid carbon residue. The smaller the volatile fraction, the more fixed carbon remains, meaning combustion energy is no longer wasted on volatile gasification reactions. Still, it is stored as high-energy fixed carbon fractions, ultimately increasing the fuel's energy density. Previous studies reported that the ideal volatile matter value for solid fuels is in the range of 5–20% by weight, depending on the pyrolysis temperature used (Chandrasekaran et al. 2024; Khater et al. 2024). This finding aligns with the research results, where the decrease in volatiles was followed by an increase in fixed carbon, from 22.26 wt% in SD to 81.15 wt% in BC and 78.46 wt% in HBC.

In terms of chemical composition, carbon content increased significantly from 22.07 wt% SD to 67.19 wt% BC and 68.61 wt% HBC, while oxygen decreased from 30.17 wt% to 19.10 wt% (BC) and 17.57 wt% (HBC). The increase in carbon and decrease in oxygen indicate a reduction in reactive functional groups (-OH, -COOH, -C=O) and a greater dominance of aromatic carbon bonds, which directly improve energy stability. These changes in element composition increase the C/O and C/H ratios, two parameters that determine the thermal stability and calorific value of solid fuels (Tomczyk et al., 2020; Wei et al., 2019). This study demonstrated an increase in the calorific value of raw biomass SD from 4155.29 cal/g to 5898.13 cal/g in BC and to 7108.29 cal/g in HBC. This value even exceeds

Table 2. Comparison of biomass product (SD, BC, HBC) and coal

Sample mark	Analysis parameters											
	Proximate (db, wt%)				Ultimate (db, wt%)						CV (cal/g)	Density (g/cm^3)
	M	Ash	VM	FC	C	H	N	O	S	Ash		
SD	17.75	29.96	30.04	22.26	22.07	4.05	0.27	30.17	0.008	43.43	4155.29	0.998
BC	3.70	5.57	9.59	81.15	67.19	4.09	1.26	19.10	0.49	7.87	5897.95	0.867
HBC	4.13	7.53	12.58	78.46	68.61	5.37	0.30	17.57	0.12	8.03	7108.23	1.103
Coal	11.29	20.55	15.82	52.34	51.96	4.47	1.21	13.06	0.76	28.54	6953.07	2.254

Note: *db = is dry basic.

the reference coal of 6953.13 cal/g, demonstrating the synergistic effect of mixing bio-oil into the biochar structure, which enriches energy density (Liu et al., 2023; M. Jahiding et al., 2024). This increase follows significant physical changes in rainfall density, SD has a density of 0.9988 g/cm3, decreasing to 0.8676 in BC due to the release of pyrolytic gases CO2, CH4, H2 and volatile compounds that cause pore cavities in the carbon structure, thereby increasing the surface area and reactivity to combustion and decreasing the volumetric energy density (Rejdak et al., 2024). However, the rainfall density increased to 1.1034 g/cm^3 in HBC. This increase proves that bio-oil functions as a pore filler and as a means of closing between particles, which can reduce the void ratio, thereby increasing volumetric energy density and combustion efficiency.

Effect of coal blending with biomass products

The analysis of coal and biomass blending results in this study aims to trigger the effect of variations in the blend ratio on the energy characteristics and thermal stability of the resulting solid fuel. Three types of biomass products were used as raw materials, namely raw biomass sago dregs (SD), biochar (BC), and hybrid biocoke (HBC), each blended with sub-bituminous coal at seven ratios to form three series of solid fuels: sago dregs-coal (SDC), biochar-coal (BCC), and hybrid biocoke-coal (HBCC), shown in Table 1. All data presented in Tables 3, 4, and 5 were obtained from direct experimental results in a standardized laboratory, including proximate, ultimate, calorific value, and bulk density tests using test methods according to ASTM standards.

Proximate analysis

Table 3 presents the results of proximate analysis on SDC (Figure 2a), BCC (Figure 2b), and HBCC (Figure 2c) samples based on variations in biomass–coal blending ratios obtained experimentally according to the ASTM D3172-98 standard. The results show that SDC (sago dregs–coal) at high biomass ratios (SDC-1 to SDC-3) has a low calorific value of 4155–4766, influenced by a high moisture content of ≥15 wt% and ash content approaching 30 wt%. This process results in a large amount of energy wasted on evaporation and solid residue. This condition increases the risk of slagging and reduces thermal efficiency. These results are consistent with research by Zhang and Yu (2025) who reported that blending coal with raw biomass reduces the calorific value by up to 15% due to high moisture content. Yin, (2020) and Yin et al. (2010) confirmed that flame stability tends to decrease at high biomass ratios. Meanwhile, at a balanced ratio (SDC-4), the calorific value increased to 4910 cal/g, but was still far below that of coal. A noticeable increase was only seen at the dominant coal ratio (SDC-5 to SDC-7), where the calorific value increased significantly, peaking at 6953 cal/g at SDC-7. This is consistent with the thermodynamic theory of combustion, which states that reducing moisture and ash increases net heat generation due to the reduced latent energy for evaporation and residue accumulation. (Sheng and Azevedo, 2005; Wang et al., 2021). Thus, SDC blending is only effective at high coal ratios, while at dominant biomass ratios, the energy quality is uncompetitive.

Ratios (BCC-1 to BCC-3), the calorific value was only in the 5898–6307 cal/g range, and flame stability was less than optimal. However, at a more balanced ratio with dominant coal (BCC-4 to BCC-7), the calorific value increased significantly to 6810 cal/g, approaching that of sub-bituminous coal. The low moisture content (less than 11 wt%) and high fixed carbon content (over 50 wt%) resulted in more stable combustion quality than SDC. Aligns with the theory that energy density is a key factor in combustion quality. According to the fuel quality theory, although biochar has a high fixed carbon content, its low bulk density (0.8676 g/cm^3) causes unstable energy per unit volume (Ngene et al. 2024; Riva et al. 2021). Other research also shows that biochar with high porosity and a large surface area tends to be volumetrically weak, making it difficult to use as a direct coal replacement without compaction (Ibitoye et al., 2024). Therefore, biochar use is more effective at low ratios because it can increase energy efficiency without compromising flame stability.

The limitations of SDC and BCC can be overcome by upgrading biochar to hybrid bio-coke (HBC), which is then blended with coal to form HBCC (hybrid bio-coke–coal). This study's results show superior performance, because almost all ratio variations have high and stable heating values in the range of 6945–7108 cal/g, equivalent to or even exceeding sub-bituminous coal. The moisture content is low at 4% to 6%, with carbon

Table 3. Experimental results of the proximate analysis and calorific values of blended product biomass-coal (SDC, BCC, dan HBCC)

Sample mark		Analisis proximate (db, wt%)				CV (cal/g)
		M	Ash	VM	FC	
SDC (Sago dregs-coal)	SDC-1	17.75	29.96	30.04	22.26	4155.29
	SDC-2	17.46	26.53	28.55	27.46	4354.13
	SDC-3	16.36	23.23	25.54	34.87	4766.29
	SDC-4	14.87	22.21	20.86	38.02	4910.07
	SDC-5	13.98	21.76	19.83	44.43	5285.35
	SDC-6	12.59	21.14	18.01	48.26	5466.85
	SDC-7	11.29	20.55	15.82	52.34	6953.13
BCC (Biochar-coal)	BCC-1	3.70	5.57	9.59	81.15	5898.13
	BCC-2	4.19	7.88	10.46	75.78	6115.63
	BCC-3	5.38	10.26	11.65	70.58	6307.57
	BCC-4	7.09	13.06	12.71	66.57	6585.57
	BCC-5	9.25	15.58	13.48	60.65	6776.29
	BCC-6	10.46	17.82	14.67	54.73	6810.29
	BCC-7	11.29	20.55	15.82	52.34	6953.13
HBCC (Hybrid biocoke-coal)	HBCC-1	4.13	7.53	12.58	78.46	7108.29
	HBCC-2	5.83	12.19	15.61	66.37	6913.85
	HBCC-3	6.37	13.98	15.68	63.97	6923.85
	HBCC-4	7.72	15.68	15.70	60.90	6930.79
	HBCC-5	8.65	17.39	15.73	58.23	6938.35
	HBCC-6	9.28	18.56	15.79	56.37	6945.35
	HBCC-7	11.29	20.55	15.82	52.34	6953.13

Note: *db = is dry basic.

maintained at around 63% to 78%. Ash content is moderate, between 14% and 18%. Of all variations, HBCC-4 (1:1 ratio) has the most balanced profile, featuring a heating value of 6,930 cal/g, carbon content of 60.90%, and the lowest ash content at 15,68%. This condition shows that at a balanced ratio, the superior properties of hybrid bio-coke are combined with the stability of coal, in accordance with the thermochemical theory, which emphasizes that high-bound carbon is the main energy source, while low moisture and ash content ensure that energy is not lost due to evaporation and residue (Yustanti et al. 2021; Rejdak et al. 2024) (Figure 3).

The advantages of HBCC are also reinforced by the theory of volumetric energy density, where the increased bulk density of hybrid bio-coke (1.1034 g/cm^3) makes it more volumetrically efficient than biochar, while improving the fuel's mechanical durability. Studi Bazaluk et al. (2022) A study by Bazaluk et al. (2022) found that integrating biomass into biocoke improves its structural strength and increases its fixed carbon value, highlighting the importance of biomass in the metallurgical industry (Baharin et al., 2020). Another interesting fact is that HBCC-1 (100% hybrid bio-coke ratio) recorded a calorific value of 7108 cal/g, higher than sub-bituminous coal, so it could theoretically replace coal completely. However, considering technological limitations and industrial-scale production costs, HBCC-3 (1:1 ratio) is considered more realistic for long-term implementation.

Ultimate analysis

The ultimate analysis, conducted based on ASTM D5373 and ASTM D2492 standards, shows fundamental differences in the composition of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) elements, which directly affect co-firing performance at each blending ratio (Kamran, 2023). In SDC (sago dregs-coal), the carbon content is relatively low (<40 wt%) and oxygen is high (>20 wt%), so the O/C ratio increases. This condition indicates that the chemical energy stored in the

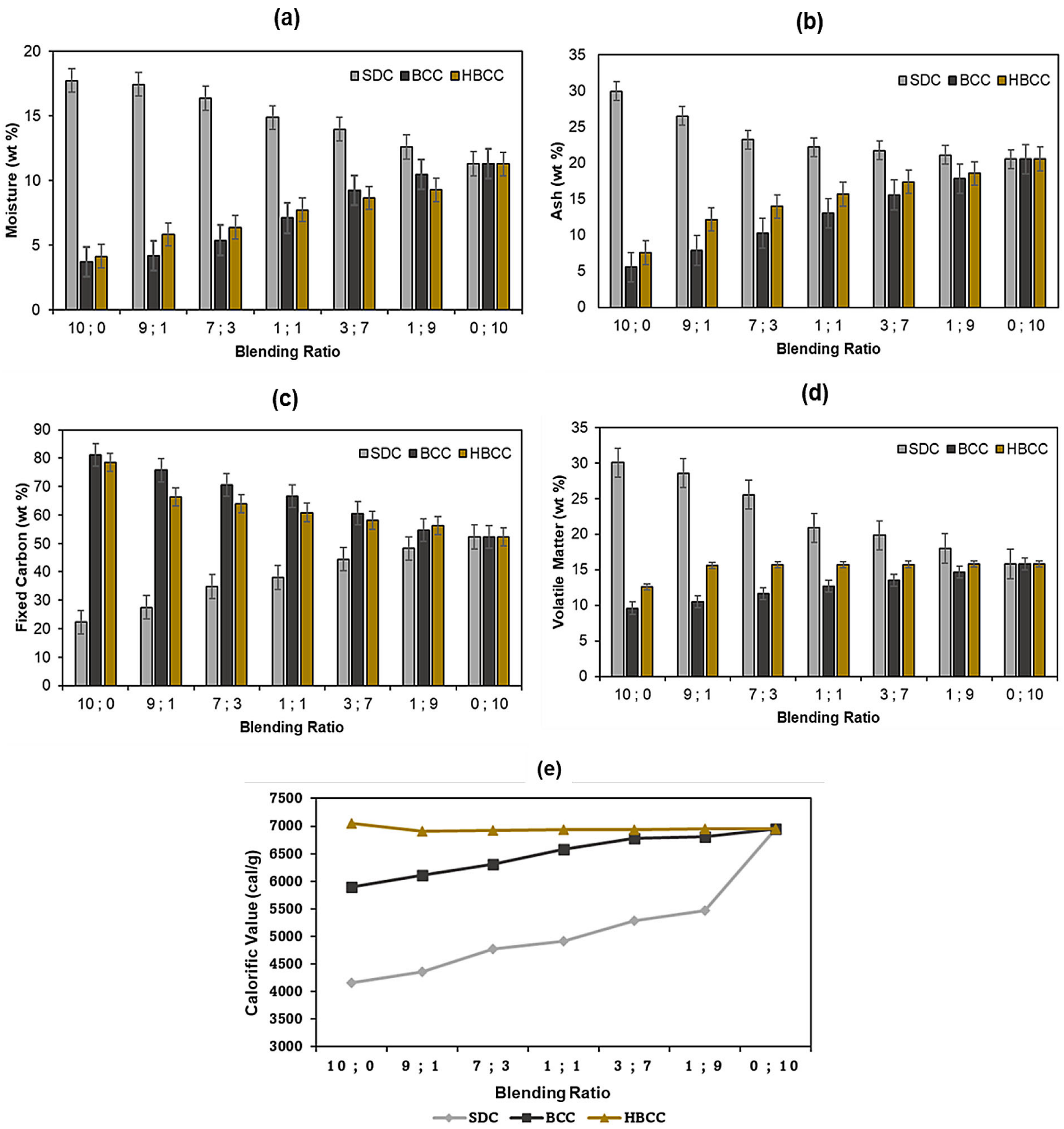

Figure 3. Effect of blending biomass and coal (SDC, BCC, HBCC) on proximate analysis: a) moisture; b) ash; c) volatile matter; d) fixed carbon, e) calorific value

C bonds is still limited, while reactive oxygen groups dominate. This situation impacts the combustion process because it requires additional energy to break oxygen bonds, resulting in low energy efficiency. Zhu et al. (2024) also reported that raw biomass-based co-firing not only reduces energy efficiency but also increases the potential for CO and NO_x emissions. Even when the coal fraction is increased, the energy quality in SDC remains hampered by significant differences in the chemical composition of biomass compared to coal.

In biochar-coal (BCC), carbon content rises to 40–55% by weight, while oxygen content decreases due to pyrolysis. This involves decarboxylation and dehydroxylation reactions that break down oxygen-containing functional groups into volatile compounds, including carbon monoxide (CO), carbon dioxide (CO_2), and water (H_2O). This reaction reduces the oxygen content in the solid and increases the carbon fraction. This mechanism is in line with the theory of lignocellulose decomposition, which states that cellulose and hemicellulose

Table 4. Experimental results of the ultimate values of blended product biomass-coal (SDC, BCC, dan HBCC)

Sample mark		Analisis ultimate (db, wt%)					
		C	H	N	O	S	Ash
SDC (Sago dregs-coal)	SDC-1	22.07	4.05	0.27	30.17	0.008	43.43
	SDC-2	26.95	4.10	0.32	28.57	0.012	40.05
	SDC-3	29.6	4.03	0.55	23.67	0.24	41.91
	SDC-4	36.71	4.20	0.74	21.46	0.38	36.51
	SDC-5	43.05	4.38	0.96	18.29	0.54	32.78
	SDC-6	47.51	4.43	1.09	15.68	0.56	30.75
	SDC-7	51.96	4.47	1.21	13.06	0.76	28.54
BCC (Biochar-coal)	BCC-1	67.19	4.09	1.26	19.10	0.49	7.87
	BCC-2	64.76	4.16	1.25	18.09	0.53	11.21
	BCC-3	61.12	4.22	1.28	17.08	0.58	15.72
	BCC-4	59.57	4.28	1.24	16.08	0.63	18.21
	BCC-5	56.65	4.27	1.23	15.07	0.67	22.11
	BCC-6	53.09	4.40	1.22	14.06	0.72	26.51
	BCC-7	51.96	4.47	1.21	13.06	0.76	28.54
HBCC (Hybrid biocoke-coal)	HBCC-1	68.61	5.37	0.30	17.57	0.12	8.03
	HBCC-2	65.63	5.22	0.45	16.83	0.22	11.65
	HBCC-3	63.12	5.07	0.61	16.06	0.35	14.79
	HBCC-4	60.29	4.92	0.76	15.32	0.44	18.28
	HBCC-5	58.86	4.77	0.92	14.56	0.54	20.35
	HBCC-6	54.21	4.62	1.13	13.83	0.67	25.54
	HBCC-7	51.96	4.47	1.21	13.06	0.76	28.54

Note: *db = is dry basic.

lose oxygen more easily than lignin (Jahiding et al., 2023; Sheng and Azevedo, 2005; Wang et al., 2021). The increase in carbon is directly proportional to the calorific value, while the decrease in oxygen reduces the O/C ratio so that combustion is more efficient. However, biochar is still not fully equivalent to coal because the C/H ratio is relatively lower, so the combustion rate is faster and the potential for volatile release remains high. Ippolito et al. (2020) and Yaashikaa et al. (2020) emphasized that the energy quality of a fuel is determined by a low O/H ratio and high fixed carbon content; biochar only partially meets these criteria because the O/H ratio is still higher than that of coal.

The hybrid biocoke-coal (HBCC) showed significant improvements in its ultimate analysis. Carbon content rose to 63.17 wt% with low oxygen, aligning the carbon-to-oxygen (C/O) ratio with sub-bituminous coal. The stable hydrogen content supported uniform flame formation, while low sulfur levels minimized SO_2 emission risks. Yustanti et al. (2021) observed that hybrid biocoke retains a high calorific value because of its dense carbon structure. Rejdak et al. (2024) confirmed that the properties of biocoke can match or even surpass those of coal, making it a more stable solid fuel. This success in upgrading highlights the benefits of integrating bio-oil into biochar, which enriches aromatic hydrocarbons and enhances the carbon structure. Thus, the main weakness of SDC in ultimate analysis is its low carbon and high oxygen content, which limits energy efficiency and increases potential emissions. BCC improves this weakness by increasing carbon and reducing oxygen, but it still suffers from fast combustion and low energy stability. HBCC tackles these issues with high carbon, low oxygen, stable hydrogen, and minimal sulfur. This makes it comparable to sub-bituminous coal and more environmentally friendly due to lower emissions. This is consistent with solid fuel reactivity theory, which states that the combination of high carbon and low oxygen has been shown to increase energy and combustion stability (Manrique et al., 2019; Seo et al., 2020).

Calorific value analysis

The calorific value is a key parameter representing the net energy capacity of solid fuels and serves as an indicator of co-firing feasibility. Calorific value testing was conducted using a bomb calorimeter according to ASTM D5865 standard. The results of this study show apparent differences in calorific value between SDC, BCC, and HBCC. In SDC (sago dregs–coal), the calorific value is relatively low at 4155–4910 cal/g when the biomass fraction is dominant (SDC-1 to SDC-3). This condition indicates the limitations of raw biomass as a fuel, because non-energy components such as water vapor and ash consume most of the energy potential. An increase in calorific value is only observed when the coal portion is dominant (SDC-5 to SDC-7), with values approaching 6953 Cal/g. Indicates that the energy contribution to SDC is more influenced by coal than by biomass, as also reported by Zhai et al. (2025), who emphasized that coal remains the primary determinant of energy performance in raw biomass-based blends.

The BCC (biochar-coal) ratio demonstrated more stable performance compared to SDC. The relative heating value increased from BCC-1 to BCC-3, reaching 5898–6307 cal/g. This increase is largely due to the conversion of raw biomass into biochar through pyrolysis, which reduces volatiles while increasing the fixed carbon content. However, this value is unstable because of biochar's low bulk density. Studies by Stelte et al. (2012) dan Ibitoye et al. (2023) indicate that biochar with high porosity, while having a more stable chemical composition, tends to be less volumetrically efficient. A more consistent increase in the heating value was observed from BCC-4 to BCC-6, reaching 6810 cal/g, nearing the heating value of sub-bituminous coal. The findings align with Seo et al. (2020), who noted that higher fixed carbon correlates with increased heating value. However, biochar struggles to compete industrially without densification.

Hybrid biocoke-coal (HBCC) showed the most stable and consistent performance when compared with sago dregs-coal (SDC) and biochar-coal (BCC). Across all ratios, the calorific value ranged from 6.945 to 7.108 cal/g. Notably, HBCC-1, which consists of 100% hybrid biocoke, achieved a calorific value of 7.108 cal/g, exceeding that of sub-bituminous coal. HBCC-4, featuring a 1:1 ratio of biocoke to coal, consistently achieved a stable calorific value of 6.924 cal/g, even with a substantial biomass content. As noted by Jahiding et al. (2025), the improved hybrid biocoke exhibited energy quality and stability comparable to that of coal, along with the additional advantage of increased density. Hybrid biocoke can maintain a high calorific value across different compositions due to its dense carbon structure (Yustanti et al., 2021). As a result, hybrid biocoke carbon (HBCC) is becoming less reliant on coal and may even surpass its energy characteristics under certain conditions.

Bulk density analysis

Bulk density is a crucial physical parameter in assessing solid fuel quality because it affects storage, transportation, mixing homogeneity, feed rate, and energy per unit volume. Bulk density testing in this study refers to the ASTM D7481-18 standard, which involves comparing the mass of dry fuel to its measured volume. Fuels with low density tend to produce unstable mass flow and increase the risk of particle segregation. Furthermore, low density also reduces volumetric energy efficiency due to the smaller fuel mass per unit volume (Dyjakon et al., 2021; Stelte et al., 2012). The results (Table 5) show that raw sago biomass (SDC) has an initial density of 0.9988 g/cm³ at a ratio of 10:0 (SDC-1), which is lower than that of sub-bituminous coal (2.2540 g/cm³). Density increases gradually with increasing coal fraction, for example, to 1.6822 g/cm³ in SDC-5 and reaches parity with coal in SDC-7. The limitations of SDC at high biomass ratios are primarily due to the low bulk density of biomass, which reduces volumetric energy density and flow/feed stability in the combustion system; this phenomenon has long been noted in the literature on biomass combustion properties (Jenkins et al., 1998) and is emphasized by Cai et al. (2017), which is a comprehensive review of biomass density & flowability and the need for densification/torrefaction to increase volumetric energy density (Chen et al., 2015; Riva et al., 2021).

Biochar-coal (BCC) exhibits a more pronounced weakness, with an initial density of only 0.8676 g/cm³ in BCC-1. This low density is due to the large porosity formed during pyrolysis. Several studies have shown that biochar is generally highly porous, so its volumetric efficiency remains low even with a high bound carbon content (Ibitoye et al., 2023). The increase in BCC density only appears significant at compositions with a higher coal fraction, for example,

Table 5. Experimental results of bulk density analysis of biomass and coal blending samples (SDC, BCC, HBCC)

Sample mark	Bulk density (g/cm³)						
	10:0	9:1	7:3	1:1	3:7	1:9	0:10
SDC	0.9988	1.0587	1.2041	1.3987	1.6822	2.0920	2.2540
BCC	0.8676	1.0368	1.2672	1.4540	1.7809	1.9518	2.2540
HBCC	1.1034	1.1797	1.7513	1.8192	1.8495	1.9608	2.2540

1.6822 g/cm³ in BCC-5, which reaches coal-like levels in BCC-7. Suggests that biochar remains difficult to utilize optimally on an industrial scale without further improvement.

HBCC showed significant improvements. Its pure state (HBCC-1) density reached 1.1034 g/cm³, higher than that of SDC and BCC. At a balanced ratio (HBCC-4, 1:1), the density increased sharply to 1.8192 g/cm³, and continued to rise to 1.8495 g/cm³ in HBCC-5, approaching that of coal in HBCC-7. This increase is due to the role of bio-oil, which acts as a binder, filling the pores of the biochar, strengthening interparticle bonds, and increasing the density of the material structure (Dyjakon et al., 2021; Ungureanu et al., 2025). Comparisons between products at identical ratios demonstrate the consistent superiority of HBCC. At a 1:1 ratio, the density of SDC-4 is only 1.3987 g/cm³, BCC-4 1.4540 g/cm³, while HBCC-4 reaches 1.8495 g/cm³. These data confirm that HBCC can produce higher densities on a significant portion of biomass, thus ensuring more stable feed rates, better mixing homogeneity, and greater volumetric energy (Sarker et al., 2023; Bajwa et al., 2018). Thus, upgrading biomass to hybrid biocoke has proven to be an effective strategy in improving chemical quality and enhancing physical properties crucial for successful industrial co-combustion applications.

CONCLUSIONS

This study proves that improving the quality of sago dregs through pyrolysis into HBC can improve the energy quality and co-firing feasibility compared to raw biomass (SD) and biochar (BC). HBC exhibits stable calorific value (6.945–7.108 cal/g), low moisture content, high fixed carbon, and better density, making its quality equal to or surpassing bituminous coal. In the blending scheme, HBCC-4 (1:1) shows the optimum formulation with a high calorific value and density of 1.8192 g/cm³ that balances energy efficiency, thermal stability, and physical characteristics, making it the best formulation for industrial implementation. These findings confirm the potential of sago dregs-based HBC as a competitive alternative solid fuel, supporting sustainable energy transition while adding value to local biomass waste.

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