STUDY ON THE APPLICATION OF BIOCHAR FROM FOOD WASTE AS SOLID FUEL PELLETS

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ABSTRACT

This study investigated the production potential of solid fuel pellets of biochar derived from coffee grounds and sugarcane bagasse sourced from food waste. The results showed that pyrolysis carbonization of coffee grounds and sugarcane bagasse positively affected energy efficiency compared to raw materials. Specifically, carbonization at 350 °C for 60 minutes yielded the highest calorific values, achieving 7,475 kcal/kg for coffee grounds and 6,990 kcal/kg for sugarcane bagasse. The mixing ratio of 90:10 between biochar and binder produced the best fuel pellets from coffee grounds, achieved the calorific value of 7,060 kcal/kg, compressive strength of 20.10 kg/cm^2, and ash content of 1.46%. These findings met the key quality criteria for using biochar as an alternative energy source to charcoal or fossil fuels.

Keywords: Biochar, bio-fuel, food waste, fuel pellets.

1. INTRODUCTION

Ho Chi Minh City, with nearly 9 million residents, has 66.7% of its population in the workforce, active in industry, agriculture, and services [1]. By late 2022, solid waste generation reached 9,500 tons per day [2], posing significant environmental and health challenges. Rapid population growth and rising energy consumption have also increased the risk of energy shortages in urban areas. If economic and ecological constraints were applied, the projection for available wood significantly decreases, and it will probably not satisfy future global energy demand. In regions that rely on biomass energy, as Africa, Asia, and Latin America, pyrolysis bioenergy provides opportunities for more efficient energy production than wood burning. It also widens the options for the types of biomass that can be used for generating energy, beyond wood, for example, crop residues or organic waste. Food waste typically accounts for 55-70% of total municipal solid waste, with the main components being leftover food (29.67%) and discarded vegetable and fruit matter (61.87%), such as banana peel, mango endocarp, seeds, orange peel, tea waste, coffee grounds, and bagasse [3, 4]. Depending on its type and composition, food waste can be treated by composting, anaerobic digestion, chemical production, combustion, pyrolysis, gasification, or landfilling [5, 6].

Coffee and sugarcane are popular brewed drinks throughout Vietnam and around the world. During the extraction of the beverages from coffee powder with hot water, or the pressing of sugarcane, a large amount of residue is produced from cafeterias and domestic production. Due to their high organic content—including carbohydrates, proteins, fibers, caffeine, polyphenols, tannins, and pectin—coffee grounds and sugarcane bagasse have been widely considered for use as animal feed, soil conditioners, and organic fertilizers. Chemically, both residues are also characterized by a relatively high carbon content (ranging from 35.65% to 56.55%) [5, 7], making them comparable with various agricultural by-products commonly utilized as efficient biomass fuels in residential and industrial applications.

Burning biomass for cooking or heating has long been widely used in domestic and industrial settings. Pyrolysis is generally described as the thermal decomposition of the organic components in biomass within an inert atmosphere at a moderate temperature to yield biochar. Biochar (BC) is a carbon-rich product obtained through biomass pyrolysis. The materials used to produce biochar include wood, stems, branches, leaves, agricultural by-products, and organic waste [8, 9]. Pyrolysis temperature and feedstock source influence the physicochemical properties of biochar, such as pH, electrical conductivity (EC), char yield, water retention capacity, elemental carbon content, zeta potential, and the transformation of cellulose, hemicellulose, lignin, as well as the inorganic composition of the material [8, 10-12]. Biochar has been widely applied to treat heavy metal-contaminated water and improve agricultural soils, as it enhances cation exchange capacity, provides multiple functional groups on its surface, and offers a relatively large specific surface area [4, 6, 13-17]. The application of biochar derived from waste as an alternative energy source has been conducted and evaluated in recent years [18-23]. However, no standard currently prescribes the composition or preparation of biochar to distinguish it from biochar produced as fuel. Moreover, using raw biomass residues as fuel presents several challenges, potentially limiting their broader application in power generation. These challenges include a large bulk volume, high moisture content, low heating value and energy density, hygroscopic nature, and smoke during combustion, all of which contribute to reduced combustion efficiency. This study investigated the thermochemical characteristics of coffee grounds and sugarcane bagasse for biochar production, which was subsequently utilized in the formation of solid fuel pellets. This process increased energy density and enhanced combustion efficiency; not only was energy obtained during the charring process, but the volume and especially the weight of the waste material were also significantly reduced.

2. MATERIALS AND METHODS

2.1. Materials

The food waste used in this study included coffee grounds and sugarcane bagasse collected from households engaged in beverage businesses in Ho Chi Minh City. The initial characteristics of the materials were presented in Table 1.

Table 1. Characteristics of the materials

No	Parameters	Unit	Materials	
			Sugarcane bagasse	Coffee grounds
1	Moisture	%	45	59.4
2	Ash	%	0.018	0.025
3	Organic Carbon	%	46.37	81.44
4	Total Calorific Value*	kcal/kg	4,380	5,130
(*)Quality Assurance and Testing Center 3 (Quartets' 3, 2024)				

The results in Table 1 show that the materials had high moisture content, which was a disadvantage for biochar production, because it can negatively impact the combustibility and heat generation [8, 23, 24]. However, the chemical properties of coffee grounds and sugarcane bagasse shown that there were low ash content, high organic carbon and calorific values, specifically 46.37% carbon and 4,380 kcal/kg for sugarcane bagasse, and 81.44% carbon and 5,130 kcal/kg for coffee grounds, these results suggest that coffee grounds and sugarcane bagasse can be applied as carbon sources for energy production [8, 9, 21, 24].

All chemicals were of analytical grade, including phosphoric acid (H_3PO_4, 85%), Ammonium ferrous sulfate ($(NH_4)_2Fe(SO_4)_2.6H_2O$, 99%), sulfuric acid (H_2SO_4, 98.0%), Potassium dichromate ($K_2Cr_2O_7$, 99%), which were purchased from Merck, Germany.

2.2. Methods

2.2.1 Preparation of materials

In this study, the coffee grounds and sugarcane bagasse were pyrolyzed in an inert atmosphere at a moderate temperature to produce biochar, which was subsequently used to create solid fuel pellets. This process was illustrated in Figure 1, follow these steps: (1) The materials were pre-treated by drying and grinding to a uniform size (d < 2 cm), and then dried at 105 °C until constant weight was achieved [23, 25], (2) Biochar production through pyrolysis of coffee grounds and sugarcane bagasse involves investigating the effects of temperature and pyrolysis time [8, 10, 11, 21, 23, 26], and (3) Mix, compress, and form fuel pellets using flour as a binder to improve adhesion and increase energy density [19, 21, 22].

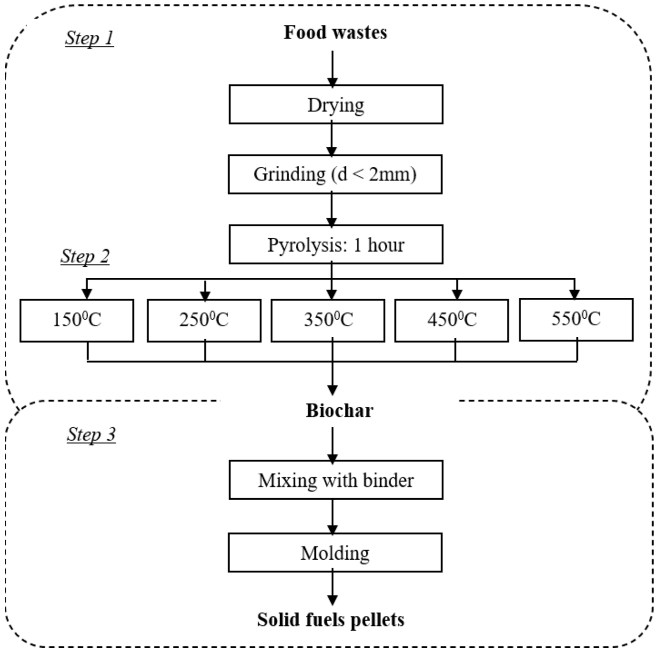

Figure 1. A diagram illustrating the process of biochar production for fuel applications.

2.2.2. Experiment design

The thermochemical characteristics of coffee grounds and sugarcane bagasse were investigated for biochar production, and applied to create solid fuel pellets, with the following experiments for each material: (1) Examining the factors affecting biochar production from sugarcane bagasse and coffee grounds involves varying the pyrolysis temperature from 150 °C to 550 °C for 1 hour [8, 10, 11, 21, 23, 26]; (2) Utilizing biochar to create solid fuel pellets by adding flour as an adhesive binder and mixing it with biochar at various ratios, specifically 10-30% by weight; (3) Compress in a cylindrical mold with a diameter of 2.5 cm and height of 10 cm (Figure 2) [9, 19]. A compressive force is applied to the sample to form the final product, directly dependent on the sample's mass and the mold's cross-sectional area (S). Accurate determination of the applied force is critical to ensuring the structural integrity and durability of the resulting product [22].

$$\text{Area (cm}^2) = \pi \times \left(\frac{R}{2}\right)^2 ; \text{ Compressive force (kg/cm}^2) = \frac{m}{S}$$

where *R* is the mold diameter (cm), and *m* is the mass applied to the sample during compression.

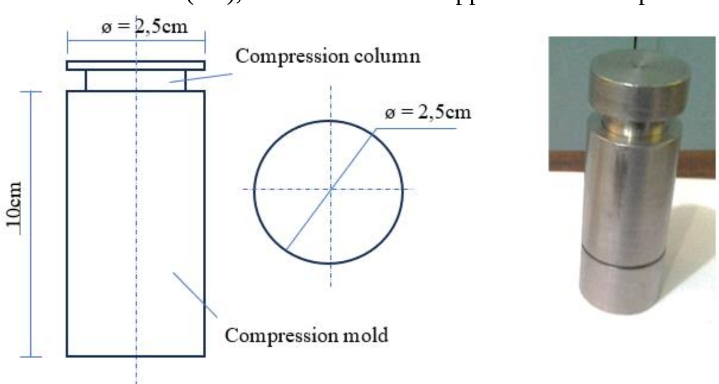

Figure 2. Compression mold

2.2.3. Analysis method

The yield of biochar was determined as the ratio of the produced biochar weight to the dry weight of coffee grounds and sugarcane bagasse subjected to pyrolysis [9, 10, 19, 21].

$$\text{Biochar yield (\%)} = (W_2/W_1) \times 100 \qquad (1)$$

where W_1 is the dry weight of coffee grounds and sugarcane bagasse sample before pyrolysis, and W_2 is the biochar weight.

The morphology and elemental composition changes of the materials before and after carbonization are determined through Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analysis using energy-dispersive X-ray spectroscopy with the JSM-IT200 (InTouch Scope). The quality of the fuel pellets is evaluated based on moisture content, calorific value, compressive strength, and ash content, by following Vietnamese standards TCVN 4919:2007, TCVN 200:2011, ASTM D695, and TCVN 173:1995, respectively.

3. RESULTS AND DISCUSSION

3.1. Effect of pyrolysis temperature on the quality of biochar derived from food waste

Biochar is the solid product of pyrolysis, which refers to the thermal decomposition of carbon-bearing compounds at elevated temperatures in the absence of oxygen. The quantity and quality of the resulting products are influenced by the composition of the biomass and the pyrolysis conditions. The yield and calorific value of biochar produced from coffee grounds and sugarcane bagasse are shown in Figures 3a and 3b. In Figure 3a, the results demonstrate that increasing the pyrolysis temperature improved biochar quality. However, higher temperatures also increased the brittleness of the biochar, which led to reduced char yield. This decrease may be attributed to the thermal decomposition of organic matter at temperatures exceeding 120 °C. Hemicellulose was decomposed between 200 °C and 260 °C, cellulose between 240 °C and 350 °C, and lignin between 280 °C and 500 °C [8, 9, 19]. As illustrated in Figure 3b, the calorific value of coffee ground-derived biochar was higher than that of sugarcane bagasse. This difference is primarily due to the higher carbon content in coffee grounds (as shown in Table 1), which plays a key role in combustion [8, 24]. Furthermore, biochar production significantly improved thermal efficiency compared to raw materials. The calorific value of raw sugarcane bagasse (4,380 kcal/kg) and coffee grounds (5,130 kcal/kg) increased to 6,990 kcal/kg and 7,475 kcal/kg, respectively, when pyrolyzed at 350 °C for 60 minutes. This temperature and duration produced the highest char yields (55–68%) and the maximum calorific values. Therefore, biochar derived from coffee grounds and sugarcane bagasse at 350 °C was selected for further analysis of its physicochemical properties and subsequent experimental studies in this research.

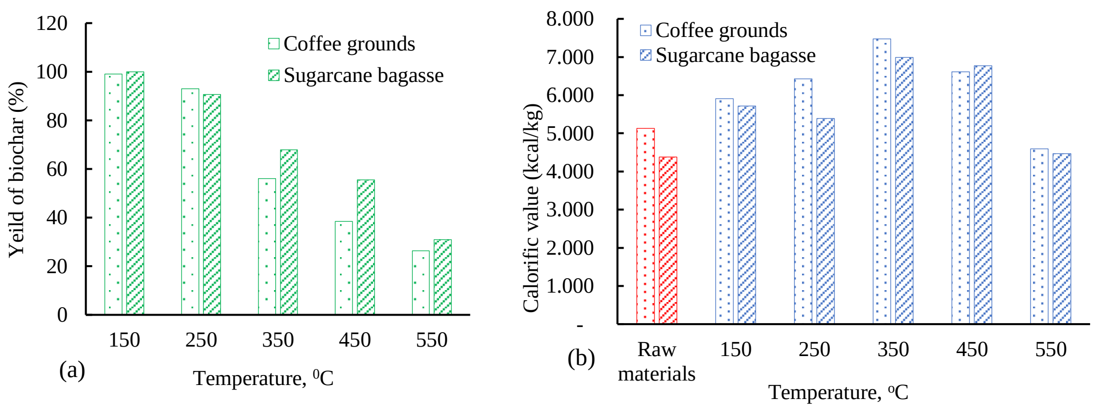

Figure 3. Effect of pyrolysis temperature on biochar products: (a) Char yields, (b) Calorific values

The morphological observation of biochar through SEM data is presented in Figure 4. The results show clear differences before and after thermal treatment. The initial images of the raw sugarcane bagasse were smooth, stacked layers (Figure 4a), and the raw coffee grounds were solid blocks (Figure 4c), while their biochar products exhibited a lot of fractures and pores (Figures 4b, d). This result may be caused by the decomposition of unstable components in cellulose and hemicellulose of materials during pyrolysis [8], leading to a reduction in the mass of biochar.

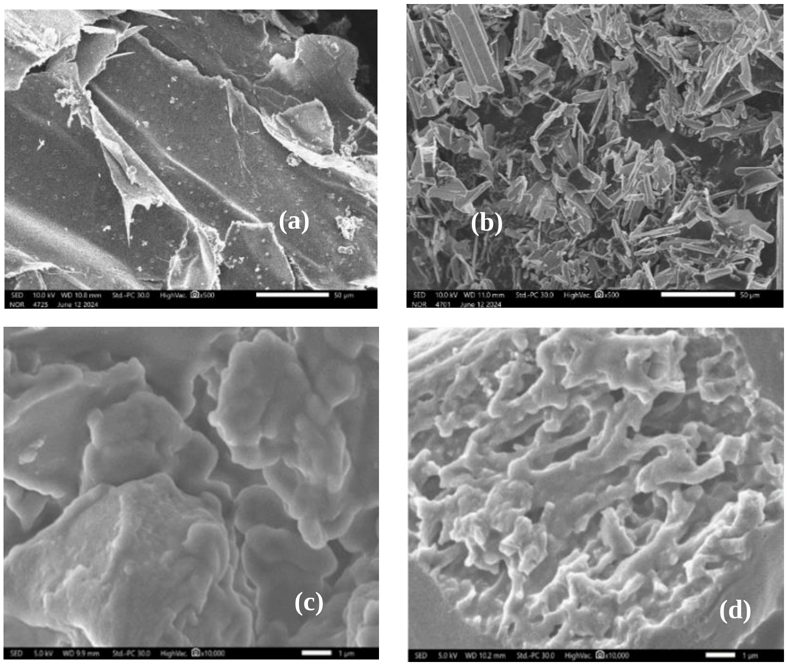

Figure 4. SEM images of the materials before and after pyrolysis. (a, b) Sugarcane bagasse and (c, d) Coffee grounds

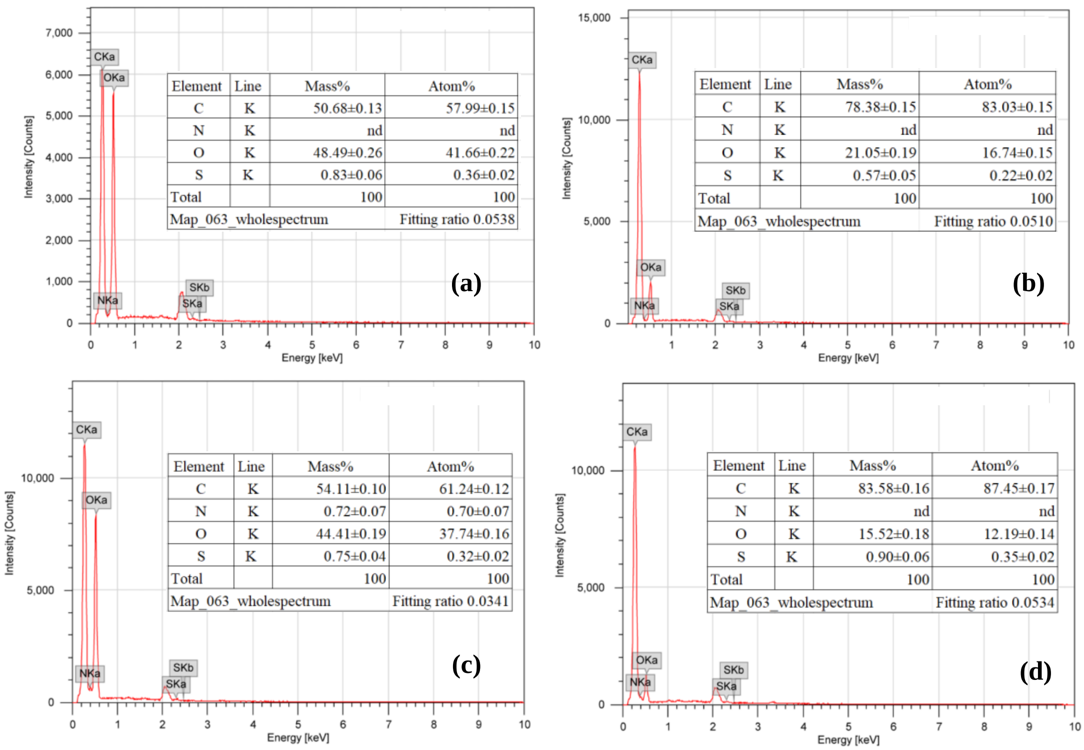

Figure 5: EDS spectra of the materials before and after pyrolysis. (a, b) Sugarcane bagasse and (c, d) Coffee grounds

EDS spectra data of biochar are shown in Figure 5. The data indicated significant changes in C, O, N, and S elements before and after pyrolysis. Specifically, the analysis showed that the pyrolysis had decreased in oxygen and a significant increase in carbon content from 50.68% to 78.38% for sugarcane bagasse (Figures 5a, b) and 54.11% to 83.58% for coffee grounds (Figures 5c, d). The pyrolysis process prevented the complete combustion of carbon, leading to the formation of a high-density carbon framework in the biochar [8, 10, 11]. Additionally, the results indicated that the nitrogen and sulfur contents in the biochar were very low (< 1%), suggesting that the material is a suitable biofuel that could help reduce greenhouse gas emissions during combustion.

3.2. Effect of blending ratio on the quality of solid fuel pellets

Biochar has a unique structure characterized by numerous small pores, which enhance air permeability during combustion. When blended with additives, this structure may be altered; however, it also facilitates the formation of solid fuel pellets, increases calorific value by binding loose materials into a compact mass, and improves storage and transportation for commercial use. From the perspective of energy utilization, particularly as a replacement for coal, the heating value of biochar is the most important fuel property [7, 14]. This study evaluated the effect of blending ratio on the quality of fuel pellets produced from biochar derived from sugarcane bagasse and coffee grounds. Biochar was mixed with a commercially available binding agent—flour—at different ratios to determine the optimal formulation. As shown in Table 2, fuel pellets made from coffee grounds exhibited a higher calorific value than those from sugarcane bagasse. The optimal performance was achieved at a 90:10 biochar-to-flour ratio, yielding 6,670 kcal/kg for sugarcane bagasse and 7,060 kcal/kg for coffee grounds. Variations in calorific values were primarily attributed to differences in carbon and ash contents. A higher ash content reduces the amount of combustible material, which can lead to slag formation in the combustion chamber and diminished heat transfer efficiency [7, 9, 26, 27]. The experimental results indicated that sugarcane bagasse had a higher ash content than coffee grounds, whereas the calorific value of the latter was superior. The calorific value of coffee ground biochar (7,060 kcal/kg) also exceeded that of conventional charcoal (5,590–6,700 kcal/kg). Across all three blending ratios, ash content remained consistently low and exhibited minimal variation among samples. Moreover, all values fell below the maximum allowable ash content specified for commercial charcoal, following Vietnamese Standard TCVN 8910:2015 [28].

Table 2. Effect of blending ratio on the combustion efficiency of biochar

Biochar type	Blending ratio of biochar: flour (%wt)	Compression pressure (kg/cm^2)	Solid fuel pellets quality		
			Calorific value (kcal/kg)	Compressive strength (kg/cm^2)	Ash content (%)
Sugarcane bagasse	90:10	0.25	6,670	16.83	1.02
	80:20		5,190	18.89	1.50
	70:30		3,930	26.93	2.17
Coffee grounds	90:10	0.25	7,060	20.10	1.46
	80:20		6,720	29.99	2.07
	70:30		5,910	45.05	2.35
Charcoal			5,590	17.03	5.25
Commercial coal according to TCVN 8910:2015 – Lump coal			6,700	-	3-16

Comparison of the physical characteristics of the fuel pellets revealed that, at an initial compression pressure of 0.25 kg/cm², pellets produced from both types of biochar demonstrated considerable structural integrity (Figure 6). The compressive strength of the pellets increased with the proportion of binding additive. Notably, pellets derived from coffee ground biochar exhibited higher compressive strength than those produced from sugarcane bagasse, with values ranging from 20.10 to 45.05 kg/cm² and 16.83 to 26.93 kg/cm², respectively. For reference, the compressive strength of conventional charcoal was measured at 17.03 kg/cm². Based on experimental data, the production cost of fuel pellets made from biochar derived from coffee grounds and sugarcane bagasse was estimated at approximately 5,100 VND/kg. This cost is substantially lower than commercial charcoal, which ranges between 8,500 and 14,000 VND/kg. Furthermore, the product is comparable to other agricultural processing by-products commonly used as biomass fuels in residential and industrial mills. This process not only generates energy during pyrolysis but also significantly reduces the volume and, more importantly, the weight of the biomass waste, thereby enhancing its feasibility for large-scale utilization.

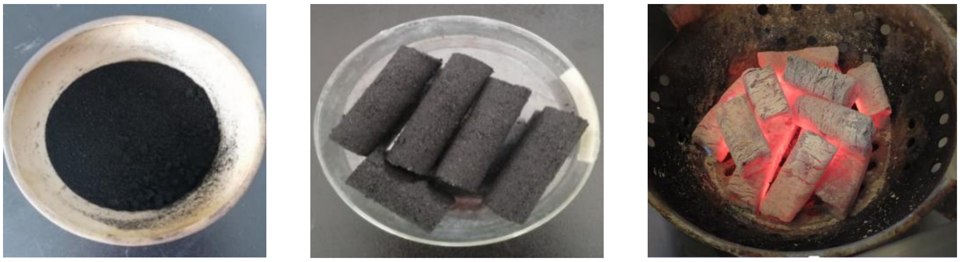

Figure 6. The solid fuel pellets are made from biochar, sugarcane bagasse, and coffee grounds

4. CONCLUSION

This study demonstrated that food waste-derived biomass, particularly coffee grounds and sugarcane bagasse, represents a promising feedstock for biochar production, exhibiting carbon contents in the range of 26.4% to 67.8%. The pyrolysis process significantly enhanced the calorific value of the resulting biochar compared to raw, untreated biomass. Higher pyrolysis temperatures improved biochar quality, but they also led to a reduction in yield. Coffee ground-derived biochar exhibited superior energy performance, achieving a maximum calorific value of 7,475 kcal/kg and a yield of 67.83% at a pyrolysis temperature of 350 °C. Optimal solid fuel pellet characteristics were obtained at a 90:10 mixing ratio of biochar to flour, resulting in a calorific value of 7,060 kcal/kg, an ash content of 1.46%, and a compressive strength of 20.10 kg/cm². These values exceeded those of conventional charcoal, demonstrating the potential of this approach for producing efficient, cost-effective, and sustainable solid biofuels from agro-industrial residues.

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TÓM TẮT

NGHIÊN CỨU CHẾ TẠO VIÊN NHIÊN LIỆU RẮN LÀM TỪ THAN SINH HỌC RÁC THẢI THỰC PHẨM

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Bài báo nghiên cứu về khả năng chế tạo viên nhiên liệu rắn của than sinh học làm từ bã cà phê, bã mía có nguồn gốc từ rác thải thực phẩm. Nghiên cứu bước đầu cho thấy việc than hoá bã cà phê, bã mía có ảnh hưởng tích cực đến hiệu quả sinh năng lượng của sản phẩm so với vật liệu thô không nung. Ở nhiệt độ nung 350 °C trong thời gian 60 phút cho nhiệt trị cao nhất, tương ứng 7.475 kcal/kg đối với bã cà phê và 6.990 kcal/kg đối với bã mía. Tỷ lệ phối trộn giữa than sinh học và phụ gia kết dính 90:10 cho kết quả viên than tốt nhất đối với bã cà phê, đạt nhiệt trị 7.060 kcal/kg, độ bền nén 20.10 kg/cm^2, độ tro 1,46% đáp ứng chỉ tiêu chất lượng của than khi sử dụng than sinh học làm nguồn năng lượng thay thế cho các loại than củi hay nhiên liệu hoá thạch.

Từ khóa: Than sinh học, rác thải thực phẩm, chất thải rắn, nhiên liệu sinh học, viên nhiên liệu.