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Characterization of Oil Palm Biomass, Derived Materials, and Applications

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Abstract: The aim of this case study is to identify the value added of existent biomass fibers (i.e., agro-industrial byproducts) and potential blends. The purpose is to explain the facts about sustainable and/or organic oil palm biomass in the energy recovery sector and in the biobased materials industry. Demand for sustainable biobased materials and energy recovery from biomass triggered the rapid growth experienced by the agricultural industry over recent years, leading to concerns about its impact on the environment and ecosystem. The agricultural industry is currently making efforts to improve sustainability practices, certifications, and to reduce carbon emissions based on innovative technologies. The used biomass, i.e. palm kernel shells (PKS), empty fruit bunches (EFB), and mesocarp fibers (MF), possesses widely accepted sustainability certifications for oil palm biomass, such as the Control Union certifications as a Roundtable on Sustainable Palm Oil (RSPO) approved certification body, the Regenerative Organic certification (ROC) for farms and products that meet the highest standards for soil health and biomass, and the EU Organic Certification in compliance with the standards and regulations of EC No. 834/2007 and EC No. 889/2008 on organic production of agricultural products. This work presents the main physicochemical characteristics of this studied biomass relevant to its energy recovery and a biobased material application. The characteristics of oil palm biomass can be summarized as a feedstock of medium energy content compared to fossil fuels and lower levels of sulfur, chlorine, and nitrogen than coal. Pellets of oil palm biomass are proven to meet expectations in both quality class A and B of non-woody pellets, i.e., characterized using the standards of solid biofuels, part 6, non-woody pellets, ISO 17225:2021. The application of biobased material ranges from pulp and paper to biobased polymer materials.

Keywords: Oil Palm Biomass, Solid Biofuel, Biobased Polymer Material, Characterization

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Introduction

Agriculture in Colombia involves a variety of different crops, of which oil palm is an important economic and social contributor. Colombia is currently the fourth largest palm oil producer in the world and the first in the Americas, with 595,722 hectares planted, producing 7,882,225 tons of fresh fruit bunches (FFB), 1,747,377 tons of crude palm oil (CPO), and 312,512 tons of palm kernel oil (PKO). This generates total sales of 1,727,572 tons, which benefits thousands of families through 197,000 direct and indirect jobs [1].

Palm oil (PO) production involves several stages starting from palm planting to the extraction of CPO and PKO. Meanwhile, this system generates different by-products with specific characteristics to satisfy certain applications and thus develops the biorefinery concept, i.e. biomass conversion into products, such as bioenergy and biomaterials. On the one hand, wastewater from PO processing is used to generate biogas; on the other hand, the solid by-products include empty fruit bunches (EFB) and mesocarp fibers (MF), which are mainly used for composting, palm kernel shells (PKS), which are widely used as solid biofuel, and palm kernel expeller (PKE), which is suitable for ruminal feed. These renewable fibers correspond to 22%, 13%, 4.5%, and 2.3% of total FFB, respectively [2], and can be upgraded to obtain higher value added products, such as pellets for animal dietary and solid biofuel or for biobased material applications.

Ensuring quality while considering environmental and social responsibility is the current driver of fair trade. Thus, certifications, such as the Roundtable on Sustainable Palm Oil (RSPO), the Regenerative Organic Certification (ROC), the Rainforest Alliance, the NON-GMO project, organic practices under the European Union standards, among others, as well as practices like the Sustainable Palm Oil Transparency Toolkit (SPOTT), are important instruments that demonstrate ethical sourcing and high quality results: regenerating soil health and farm ecosystem; zero deforestation and biodiversity conservation; water, chemical, and pest management; community, land, and labor rights; among others.

The aim of this paper is to present the main physicochemical characteristics of oil palm biomass (OPB): EFB, MF and PKS, which are the most suitable for energy recovery and biobased material applications. The OPB will be characterized by lignocellulosic content (lignin, cellulose, hemicellulose), proximate analysis (fixed carbon, volatile matter, moisture, ash content), ultimate analysis (C, H, N, O), minor compounds (Cl, S), and calorific value. Furthermore, a case study on solid biofuel pellets will be expanded to show their suitability for energy recovery.

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Materials and Methods

Sample Collection

The oil palm by-products EFB, MF, and PKS from sustainable plantations were collected according to the ISO 18135:2017 standard at the C.I. Tequendama SAS oil extraction plant in Fundación, Magdalena, Colombia, following the local plantation's internal sampling plan, to produce bio-pellets.

Biomass Physicochemical Characterization

Biomass sample preparation and determination of moisture, ash, and bulk density were performed following ISO standard 17225-6:2021. Proximate analysis was determined by a thermogravimetric method (TGA), in which the samples were treated in a two-stage process. In the first stage, under a nitrogen atmosphere to prevent burning, the samples were heated from room temperature to 120°C at a rate of 50°C/min. This stage was followed by a 3-minute isotherm at 120°C. In the second stage, the environment was switched to air and the temperature was further increased to 950°C at a rate of 100°C/min. On the other hand, carbon, hydrogen, and nitrogen content for the ultimate analysis was carried out according to the ASTM D5373-14 standard. Sulfur content was determined according to the ASTM D4329-18 standard and, based on the results, the oxygen content is calculated by difference. OPB calorific values were determined according to the ASTM D5865 standard. Furthermore, biomass pellets diameter, length, moisture, ash, mechanical durability, and bulk density were characterized according to ISO standard 17225-6:2021.

Results and Discussion

Colombian Biomass Characterization

A literature review was conducted to investigate the lignocellulosic composition of various Colombian biomass. OPB were compared to pine wood and sugar cane bagasse (SCB), common plantations in Colombia. Understanding this information is crucial for determining biomass suitability for various applications, such as biofuel production or biobased material development (Figure 1).

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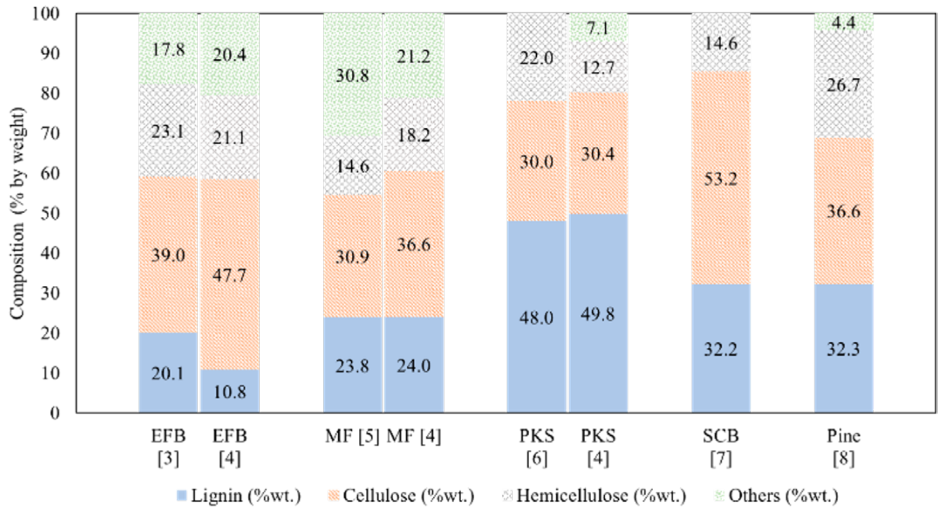

Figure 1. Lignocellulosic material from OPB: EFB, MF, PKS compared to SCB and pine wood.

Proximate analysis results (Figure 2) reveal several key characteristics of the OPB. Notably, all three types (EFB, MF, and PKS) have low ash content (EFB: 2.2%, MF: 3.1%, PKS: 1.4%) compared to sub-bituminous coal (Coal-SB: more than 9.2%) typically used in boilers. Moisture content varies across the samples. EFB and MF exhibit higher values (25% and 26%, respectively), while PKS has a lower moisture content (12.7%) analogous to Coal-SB. However, due to its biomass nature, PKS still requires drying to prevent fungal and microbial growth. In terms of volatile matter, both EFB and MF have values comparable to SCB. PKS, with 66.4% volatile matter, is quite similar to pine wood biomass. Finally, the fixed carbon content of the OPB is lower than pine wood or coal, but is still at least three times higher than the reported value for SCB.

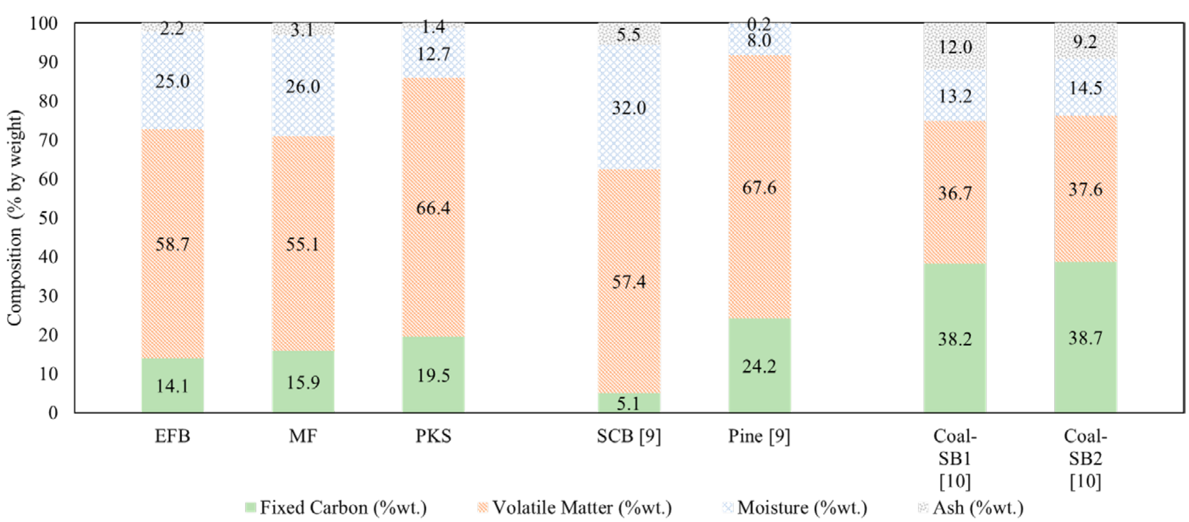

Figure 2. Proximate analysis of EFB, MF, PKS compared to SCB, pine wood and two sources of Coal-SB.

Ultimate analysis revealed key differences in the elemental composition of the OPB compared to Coal-SB, SCB, and pine wood (Table 1). Notably, EFB and PKS exhibited the highest oxygen content (44.2% and 41.5%, respectively), while MF oxygen content (38.8%) resembles SCB and pine wood. In terms of carbon content, EFB had the lowest value (45.9%), while MF and PKS possess 49.7% and 50.5%, respectively, which are comparable to Coal-SB. The most significant difference between the OPB and conventional coal was the sulfur content. The OPB had one order of magnitude lower sulfur content compared to the values presented in Table 1 for conventional coal. The OPB had lower levels of sulfur, chlorine, and nitrogen in compliance with ISO standard 17225-6:2021.

Table 1. Ultimate analysis of EFB, MF, PKS compared to SCB, pine wood, and two sources of Coal-SB.

	Composition					
	C (%wt.)	H (%wt.)	O (%wt.)	N (%wt.)	S (%wt.)	Cl (%wt.)
EFB	45.9	5.9	44.2	0.68	0.09	0.25
MF	49.7	6.5	37.9	1.41	0.15	0.27
PKS	50.5	5.8	41.5	0.39	0.07	0.11
SCB [9]	45.4	6.1	39.3	1.03	0.04	
Pine [9]	54.7	7.1	37.3	0.67	0.01	
Coal-SB1 [9]	62.2	4.5	18.0	1.25	1.71	
Coal-SB2 [9]	51.9	5.5	23.6	0.98	1.50	

Calorific value, in this case the higher heating value (HHV), corresponds to the upper limit for heat energy that can be released by a sample and is a crucial factor for evaluating the viability of biomass as a solid fuel. As shown in Figure 3, the calorific values of OPB (19.3–21.3 MJ/kg) are higher compared to SCB and pine wood, commonly used as solid biofuels. Even the calorific values of PKS, 21.3 MJ/kg, and MF, 20.5 MJ/kg, are comparable to reported values for Coal-SB, revealing their potential as sustainable solid biofuel alternatives. The calorific value of polyethylene terephthalate (PET) is shown as a basis of comparison.

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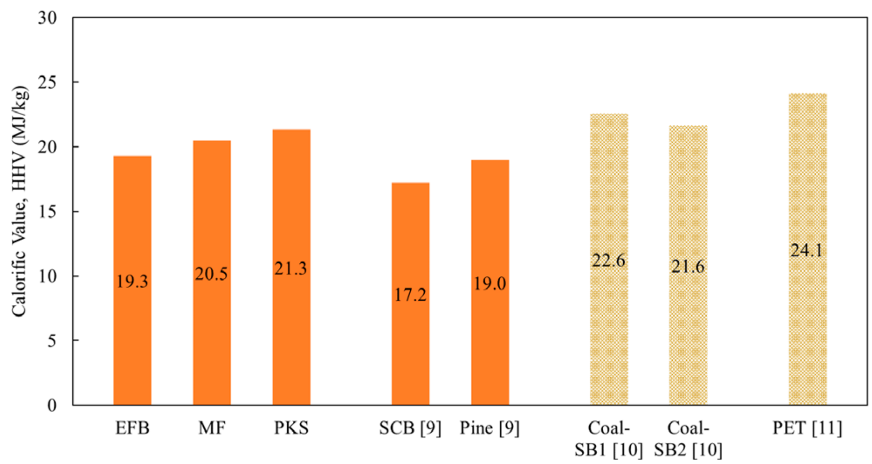

Figure 3. HHV of EFB, MF, PKS compared to SCB, pine wood and two sources of Coal-SB.

Case Study: Solid Biofuel Pellets

This case study describes some results from the project developed at CI Tequendama SAS, in partnership with the Daabon Group and the Universidad Nacional de Colombia. Pellets blends of PKS and/or MF for energy recovery were compared to ISO 17225-6 Class A and B solid biofuels specifications for non-woody pellets (see Table 2), as well as to SCB and pine wood pellets from the literature (see Table 3).

During pellet formation, the bulk density and moisture content are the most critical variables for pellets densification and its final quality. Bulk density is related to the potential for storing and long-range transporting of solids; the higher the value, the more the material can be transported or stored. This stands for logistic improvement and carbon footprint reduction. Moisture content of PKS/MF pellets blends and 100% pure MF pellets ranged from 9.1 to 12.08%, indicating compliance with ISO 17225 Class A. Nevertheless, this characteristic depends on the inlet moisture of the raw material, which could be controlled.

Table 2. OPB pellets from PKS and/or MF compared to ISO 17225-6 Class A and B solid biofuels specifications for non-woody pellets.

	Standard		Oil Palm		
	ISO 17225-6:2021		Solid Biofuel Pellets		
Parameter	Class A	Class B	Blend 1 PKS/MF	Blend 2 PKS/MF	MF100
Diameter, mm	6 to 25 ± 1	6 to 25 ± 1	8.11	8.16	8.19
Length, mm	3.15–40	3.15–40	9.28	13.64	14.13
Moisture (% Wet basis)	≤ 12	≤ 15	12.08	11.94	9.1

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	Standard		Oil Palm		
	ISO 17225-6:2021		Solid Biofuel Pellets		
Parameter	Class A	Class B	Blend 1 PKS/MF	Blend 2 PKS/MF	MF100
Ash (% Dry basis)	≤ 6	≤ 10	3.61	4.63	4.63
Mechanical Durability (%)	≤ 97.5	≤ 96.0	93.4	91.78	90.43
Calorific value (HHV), MJ/kg	≥ 14.5	≥ 14.5	20.63	20.55	20.46
Bulk density, kg/m³	≥ 600	≥ 550	685.14	691.45	679.09

Table 3. OPB pellets from PKS and/or MF compared to SCB pellets and pine wood pellets.

	Oil Palm			Other Biomass	
	Solid Biofuel Pellets				
Parameter	Blend 1 PKS/MF	Blend 2 PKS/MF	MF100	SCB Pellets [12]	Pine Wood Pellets [13]
Diameter, mm	8.11	8.16	8.19	9.7	
Length, mm	9.28	13.64	14.13	22.7	
Moisture (% Wet basis)	12.08	11.94	9.1	5.49	7.29
Ash (% Dry basis)	3.61	4.63	4.63	8.7	0.33
Mechanical Durability (%)	93.4	91.78	90.43	98.2	97.52
Calorific value (HHV), MJ/kg	20.63	20.55	20.46	18.35	20.03
Bulk density, kg/m³	685.14	691.45	679.09	726.32	713.18

Ash content is an important characteristic when evaluating a material's potential for use in boilers, the lower the ash content, the better performance into the boiler. PKS/MF pellets blend and 100% MF pellets feature ash content values ranged from 3.61 to 4.63% according to ISO 17225 Class A. In contrast, SCB pellets report 8.7% of ash content, showing Class B. These biomasses are also compared to pine wood pellets, with only 0.33% ash content. It is important to note that wood pellets must meet other standards, and their values are shown for reference only.

The decisive issue up to this point is related to the need to densify the raw material into a pellet. Figure 4(a) presents the bulk density (BD) and energy density (ED) of raw OPB. It shows the clear reason for preferring to use PKS as solid biofuel: the raw material has a BD of 483 kg/m³ with an ED of 10299 MJ/m³. Nevertheless, in the case of EFB and MF, both the BD and ED are exceptionally low: BD is 30 and 75 kg/m³ for EFB and MF, respectively, while ED is 573 and 1524 MJ/m³ for EFB and MF, respectively. However, after pelletization (Figure 4[b]), all PKS/MF pellets blends and pure 100% MF pellets achieve BD values higher than 600 kg/m³, indicating compliance with

ISO 17225 Class A. Consequently, ED also increases up to 14206 MJ/m³ in the case of Blend 2, achieving an amount close to pine wood pellet ED which is 14285 MJ/m³. In Figure 4(b) is also noticeable that all OPB pellets exceed the 13328 MJ/m³ ED of SCB pellets, indicating that not only is a high BD necessary, but that the calorific value also plays an important role.

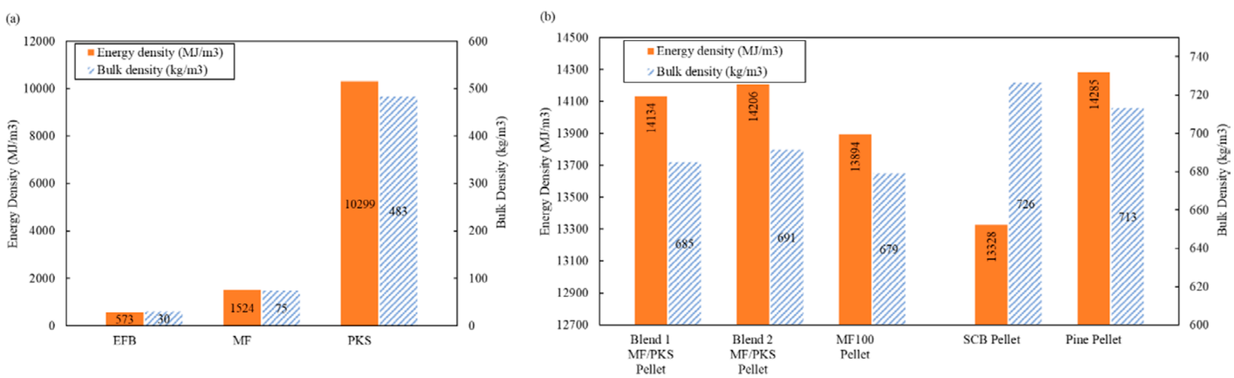

Figure 4. Energy density and bulk density of (a) EFB, MF, PKS OPB; (b) Pellets blends of PKS and/or MF compared to SCB pellets and pine wood pellets.

Conclusion

Oil palm is a sustainable oil crop from which many products could be obtained by implementing a biorefinery [14]. Current certifications related to organic farming and good social and ethical practices show the responsibility of manufacturers to the environment and the ecosystem. This work has shown that biomass from oil palm fulfils the required characteristics to be used in the energy recovery sector and in the biobased materials industry. From the proximate, ultimate, and minor compounds analysis, as well as the calorific value, it is concluded that the characteristics of OPB are comparable with those of SCB, pine wood, and subbituminous coal. In addition, the case study proves that OPB pellets could be used as sustainable solid biofuels analogous to SCB pellets and pine wood pellets. On the other hand, the lignocellulosic characterization of the different OPB fractions shows a structural difference which is suitable for developing biobased materials ranging from pulp and paper to polymeric composite materials.

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