From biomass waste to climate action: characterizing of bioenergy pellet from oil palm fronds and branches wood of mangrove

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Abstract. To support climate action by reducing emissions and transitioning from fossil fuels to renewable energy, this study focuses on producing biomass pellets as a bioenergy source. The objective is to evaluate the quality of pellets made from a mixture of oil palm fronds and mangrove branch wood. Oil palm fronds are an abundant, daily-available agricultural residue that remains underutilized, making them a promising bioenergy feedstock. Method in this study was included: the biomass was compacted into pellets using tapioca as a binder, followed by characterization of the resulting pellet properties. Initial results showed that the pellets had a denser morphology and improved specific gravity. However, pellets made solely from oil palm fronds did not meet the minimum Indonesian calorific value standard (SNI 8021:2020), which requires >4000 cal/g. To meet this requirement, mixing with high-calorific biomass such as branches wood of *Rhizophora mucronata* (4028–4047 cal/g) was necessary. Although the study is ongoing, findings confirm that oil palm fronds can be converted into bio-pellets, though the mixing ratio needs optimization. This approach promotes the use of agricultural waste, preserves mangrove sustainability by using only branches, and supports energy transition efforts—particularly for household cooking fuel—while contributing to climate change mitigation.

1 Introduction

Indonesia has been committed to re-establishing its energy independence by redirecting energy resources from exports to the domestic market, aiming to rebalance the energy mix towards indigenous energy supplies, involving lowering fossil fuel consumption with the objective is to incorporate a minimum of 23% New and Renewable Energy (NRE) by 2025 [1]. This initiative advances the United Nations Sustainable Development Goals (SDGs) number 7 and 13 by fostering sustainable bioenergy sources and diminishing dependence on

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fossil fuels, therefore promoting global aspirations to mitigate climate change. The potential of NRE in Indonesia comprises of solar/ sunlight, hydropower including water flow, waterfall and micro-hydro, wind, geothermal, hydrogen, nuclear, hydro-kinetic ocean and ocean thermal energies, and bioenergy [2].

Bioenergy can be produced with different converting technology, such as biological methods (anerobic digestion, transesterification, fermentation, microbial fuel cell) or physicochemical methods (pyrolysis, gasification, incineration, hydrothermal carbonization, landfill) results in liquid and gas as we called as biofuels like bioethanol, biodiesel, and biogas as well as solid form like firewood, charcoal, briquette, and pellet. All of these can produce feedstocks derived from biomass residue such as waste products, lignocellulosic materials, and agricultural residues [3]. According to case report on the prospects for renewable energy sources from biomass residue, Indonesia may generate up to 57 GW electricity from biomass [4] by built power plants which use forest plantations, livestock waste, papermill waste, urban waste, and industrial palm oil waste or oil palm plantation residue. These biomasses are spread out in all region of Indonesia and contains three main contents, namely lignin, cellulose, and hemicellulose.

Oil palm midribs or oil palm fronds (OPF) are considered as daily residue of the oil palm plantation. The content of cellulose, hemicellulose, and lignin are 52%, 12%, and 36%, respectively with the proximate analysis of moisture content of 11%, volatile matter of 66%, and fixed carbon of 18% and ultimate analysis of carbon (45%), hydrogen (6.54%), nitrogen (0.09%), and oxygen (46%) with high heating value of 22.65 MJ/kg [5] which potential to be solid bioenergy feedstock. In this context, OPF will be utilized further as solid bioenergy feedstock since the leaflet of oil palm leaves (OPL) has been utilized as feeding cattle and the OPF has been remaining in the site. Therefore, in this study, OPF could be utilized as source of solid bioenergy in the form of pellet, because of the abundant resources as well as sustainability of the materials. The pellet exhibits distinct combustion characteristics, including easier ignition under well-ventilated conditions, higher heat transfer rates, and more efficient combustion, resulting in a shorter overall burning time. Different range of device applications can be used for pellet such as pellet stove, furnace, or cooking appliances.

To support climate action by reducing emissions and transitioning from fossil fuels to renewable energy, this study focuses on producing biomass pellets as a bioenergy source. In this study, micro-architecture and miniature properties of the bio-pellet made of OPF were investigated since both characteristics are crucial in determining their physical, mechanical, and chemical characteristics [6]. The objective of this study is to evaluate the quality of resulted bio-pellets in term of their micro-morphological and microstructural characteristics.

2 Materials and methods

Materials of this research were OPF originated from daily residue of oil palm plantations. The OPF without the leaflets were air-dried under sunlight then converted into particle size using a conventional milling machine. In order to obtain a uniform size, a 20-mesh sieve has been applied. The particles that passed through the sieve were collected and used as samples for subsequent pellet manufacturing.

The process of pellet making was conducted via typical pelletizer machine driven by a Shark engine with a maximum capacity of 8 HP and a pulley rotation speed of 2600 rpm as carried out by [7]. The pellet material, water, and 10% tapioca starch as the binder were introduced into a pelletizing chamber. At this stage, a mechanical process occurred within the rotating pelletizing chamber, pulverizing the raw material against the cutting tool. Pellets ejected from the die holes are uniformly sized by a knife positioned beneath the die. Following the molding process, the pellets retained moisture, necessitating drying prior to

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achieving increased density and hardness. The drying procedure utilized a traditional method, wherein pellets were air-dried under direct sunlight for 3 days.

Analysis both the micro-morphology and the microstructure properties of the resulted pellets was performed using a scanning electron microscope (SEM) type TM 3000, with different magnifications hoping the results can predict their physical-mechanical characteristics [6]. The observation focused on the fracture surfaces of both the OPF raw material and the resulting bio-pellet to reveal their actual conditions. Comparison both different images with different magnifications were presented. The calorific value of bio-pellets produced from a mixture of OPF and *Rhizophora mucronata* branch wood, exceeding 4000 cal/g, will be reported in upcoming publications."

3 Results and discussions

Figure 1 showed comparison between raw materials of OPF and resulted bio-pellets with different magnification, namely low (500x magnifications), moderate (1000x magnifications), and high (3000x magnifications).

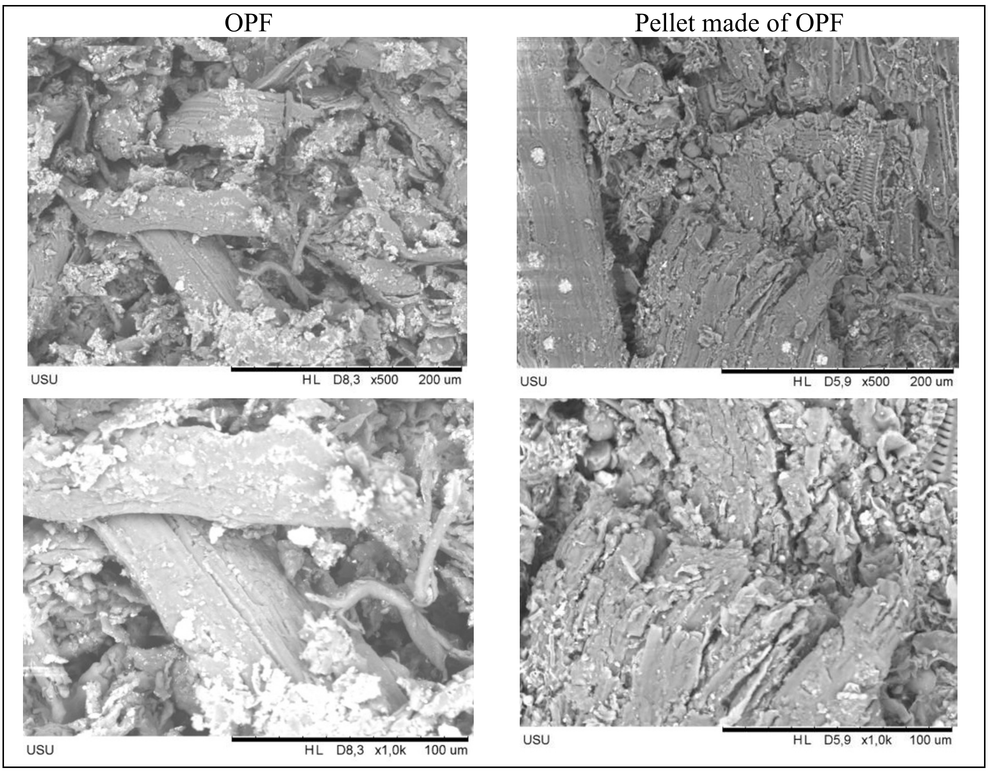

Fig. 1. Comparison of images with different magnifications (low, moderate, and high) between raw material OPF and resulted pellet.

Initial results showed that the pellets had a denser micro-morphology compared to the raw materials of OPF as depicted in Fig. 1 (upper) thus improved specific gravity. Comparing with another SEM image with same magnification [8], the micro-morphology was distinct in term of the arrangement. In this work, fracture surface of the raw material of OPF was observed while the image from [8] probably derived from a section from a hand section using a razor blade/ knife cutting or a sliding microtome as a procedure standard in sample preparation of SEM [9]. With higher magnifications (middle and bottom), the micro-morphology and micro-structure both the objects were apparent. OPF showed many vessels, voids and cavities as previous works also mentioned [10] while resulted pellets showed denser structures. Distinct structure was seen in moderate magnification, when it was observed using high magnification, the structure showed integrated structure with considerable pores as mentioned in previous study [11]. This structure is similar with pore vessel element or a perforation vessel with scalariform types similar in wood tissue [12]. The existence of this kind of vessel indicated that raw material of pellet was not homogeneous comprised of particles derived from fibers of the OPF. Another feature such as vessel contributed the heterogeneous of the composition of the pellet. Therefore, when the pellets made solely from OPF, they did not meet the minimum Indonesian calorific value standard (SNI 8021:2020), which required more than 4000 cal/g.

Therefore, for fulfilling standard requirement, mixing with high-calorific biomass such as branches wood of *Rhizophora mucronata* (4028–4047 cal/g) was necessary. We intended to use only the branches parts for keeping the mangrove forest sustainable. First attempt to mix with mangrove biomass of branches wood, resulted in denser morphology as depicted in Fig 2.

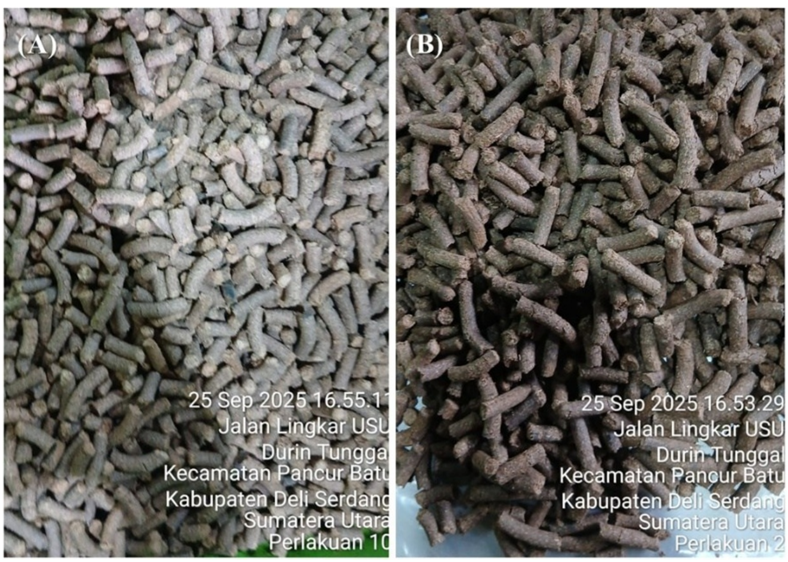

Fig. 2. Typical bio-pellet made of 100% OPF particles (A) and bio-pellet made of 80% OPF and 20% wood branches of mangrove of *R.mucronata* (B).

Even though the study is ongoing, findings confirmed that OPF can be converted into bio-pellets, and the mixing ratio required optimization. This approach promotes the use of agricultural waste, preserves mangrove sustainability by using only branches, and supports energy transition efforts—particularly for household cooking fuel—while contributing to climate change mitigation.

4 Conclusions

For concluding remarks, the utilization of OPF as raw material of solid bioenergy such as pellet, could help transitioning from fossil fuels to renewable energy. Even though mangrove branch wood was incorporated to enhance the calorific value of the pellets, it was added in a limited amount solely to satisfy the minimum standard requirements. Micro-morphologically the resulted pellet was denser, more uniform, and having high calorific value as the prediction of the physical properties of the bio-pellet. Therefore, this effort supports climate action by reducing emissions and transitioning from fossil fuels to renewable energy.

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