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Oil palm waste: An abundant and promising feedstock for microwave pyrolysis conversion into good quality biochar with potential multi-applications

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ABSTRACT

Oil palm waste (OPW), comprising mainly of empty fruit bunch, mesocarp fiber, frond, trunk, and palm kernel shell generated from palm oil industry, was collected, characterized, and then pyrolyzed to evaluate their potential to be converted into biochar with desirable properties for use in multi-applications. The OPW was detected to have considerable amounts of carbon (43–51 wt%) and fixed carbon (30–39 wt%), showing potential to be converted into carbon-rich biochar. Microwave pyrolysis of palm kernel shell as the selected OPW produced a biochar with zero sulphur content and high heating value (23–26 MJ/kg) that is nearly comparable to conventional coal, thus indicating its potential as an eco-friendly solid fuel. The biochar obtained was also showed low moisture (<3 wt%) and ash (3 wt%), and a highly porous structure with high BET surface area (210 m^2/g), indicating the presence of many adsorption sites and thus showing desirable characteristics for potential use as pollutant adsorbent in wastewater treatment, or bio-fertilizer to absorb nutrient and promote plant growth. Our results demonstrate that OPW is a biowaste that shows exceptional promise to be transformed into high-grade biochar rather than simply disposed by landfilling or burned as low-grade fuel in boiler.

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1. Introduction

Oil palm plantations occupy the largest sector of agriculture in Malaysia with approximately 5.7 million hectares of plantation area in 2016 (MPOB, 2017). The subsequent processing to produce palm oil inadvertently produces great amount of oil palm wastes (OPW) that generally comprise of 15% of mesocarp fibres (MF), 6% of palm kernel shells (PKS), and 23% of empty fruit bunches (EFB) in one ton of fresh fruit bunch (FFB) of oil palm (Loh, 2016; Omar et al., 2011). According to Malaysia Palm Oil Board (MPOB) (Board, 2017), the total production of crude palm oil (CPO) in Malaysia was 3.4 million tonnes in 2016, hence about 25.5 million tonnes of OPW were generated since 75 wt% of the solid wastes were produced from 10 wt% of CPO.

The majority of OPW (e.g. PKS and MF) are currently burned in boiler to generate steam for sterilization of fresh fruit bunch, however this method could lead to air pollution by releasing flue gases containing ash, CO, and NO_x into the atmosphere (Okoroigwe et al., 2013). OPW is also used as combustion feedstock for electricity generation in some palm oil mills, which leads to production of undesirable ash (Awalludin et al., 2015). It is thus thought that an alternative method should be developed by transforming OPW into value-added materials such as biochar or activated carbon to improve the recovery of OPW and divert these wastes from landfill or being a source of air pollution.

Pyrolysis, a thermal decomposition process under an inert environment, shows potential as an environmental friendly method to treat OPW (Lam et al., 2016a). Combustion of waste can release significant amounts of greenhouse gases such as carbon dioxide (CO_2), whereas pyrolysis method can limit the production of greenhouse gases and decompose the waste to produce potentially useful products comprising of solid biochar, liquid bio-oil and biogas (Lam et al., 2016b). These products can be used as chemical feedstock, fuel source, soil amendment, catalyst, or further upgraded into activated carbon (He et al., 2017; Lam et al., 2016d; Lee et al., 2017a; Tan et al., 2017). In particular, microwave pyrolysis, a pyrolysis technique using microwave heating as the heat source, has recently been investigated for its potential for waste recovery.

Microwave pyrolysis offers a rapid and selective heating mechanism over other thermal decomposition processes (e.g. conventional pyrolysis, gasification and combustion) (Al-Salem et al., 2017; Lam et al., 2017b; Salema et al., 2017). The use of microwave radiation targets mainly to carbon-based material with good microwave absorbency. When the carbon material is exposed to microwave radiation, dipole rotation in atomic scale is occurred up to million times per second within the material. As a result, heat energy is rapidly generated from the frictions between the atoms and molecules within the material which subsequently leads to fast heating of the material, thus shorter process time (<30 min) is required to heat up the material to achieve a desired high temperature (Lam and Chase, 2012; Wan Mahari et al., 2016). By comparison with the conventional pyrolysis that is heated by a furnace, the heating mechanism is non-selective where the heat energy targets everything within the chamber of the furnace. The heat energy is transferred from the heating coil of the furnace to the sample mainly by conduction and convection mechanisms, which are comparatively slower than microwave pyrolysis, thus longer process time (>1 h) is needed to heat up the sample until the desired temperature.

In this study, the biochar produced from microwave pyrolysis of OPW is of interest due to its potential to be used in many applications. The characteristics and yield of the biochar obtained depend on the types of feedstock used and process parameters involved. For instance, the yield of biochar is significantly affected by process parameters such as heating rate and residence time (Tripathi et al., 2016a). Fast heating rate (up to 100 °C/min) with short residence time (from seconds to minutes) favour the formation of liquid bio-oil with less biochar obtained. In contrast, slow heating rate (5–10 °C/min) with long residence time (up to 1 h) were reported to enhance the yield of biochar (Collard and Blin, 2014).

The biochar produced usually possesses better adsorption property compare to its raw material due to the characteristic of porous surface structure with wide range of surface area (10–300 m^2/g). In addition, the surface chemistry of biochar that has high carbon content can be altered by introducing several chemical functional groups (e.g. hydroxyl and carbonyl) for specific adsorption purpose (Angin et al., 2013). Due to its unique characteristics, it has been researched for its application in removal of heavy metal (Godinho et al., 2017; Johari et al., 2016), production of H_2 gas using gasification (Lv et al., 2016), as catalyst in catalytic pyrolysis reaction (Seng-eiad and Jitkarnka, 2016), as soil additive to improve microbial respiration response (Lanza et al., 2016), or it can further be upgraded into activated carbon that has wider applications as supercapacitor, humidity regulator, and protector of electromagnetic radiation (Gupta et al., 2015; Tripathi et al., 2016b; Zhang et al., 2016).

In view of the large production of OPW and the advantages shown by the biochar produced from pyrolysis process, this study was performed to investigate the potential of using OPW as a pyrolysis feedstock for recovery of biochar with desirable properties for use in multi-applications. This included some in-depth analyses of the elemental and proximate composition of the OPW. The wastes were then analyzed via a thermogravimetrical approach to examine the different types and stages of chemical reactions (e.g. moisture evaporation, devolatilization, fragmentation) that could occur during their thermal decomposition by pyrolysis, and to propose the suitable pyrolysis temperature for optimal recovery of biochar. The OPW with desirable properties was selected and pyrolyzed to produce biochar over a range of microwave power considered. The biochar obtained was then analysed for their various properties (i.e. chemical compositions, surface morphology and porous characteristics) followed by examining its applications as dye adsorbent and bio-fertilizer in mushroom cultivation in order to assess its potential to be used in multi-applications. There have been studies reported on pyrolysis of OPW, however most of them focused on the recovery of bio-oil and biogas as fuels (Hossain et al., 2016a,b; Khanday et al., 2016; Tan et al., 2016; Yin et al., 2016). To the best of our knowledge, there has yet to be any studies reported on the use of vacuum environment to perform microwave pyrolysis. Pyrolysis performed under vacuum environment could provide advantages in preventing uncontrolled heating inside the reactor and avoiding adverse chemical reactions such as re-condensation of volatiles on the surface of the biochar.

2. Materials and methods

2.1. *Source and preparation of oil palm wastes (OPW)*

Five types of OPW, namely empty fruit bunch (EFB), palm kernel shell (PKS), mesocarp fiber (MF), trunk, and frond, were collected from palm oil mill located in Kemaman, Terengganu, Malaysia. The OPW collected were rinsed with tap water to remove dirt particles and dried in an oven for 24 h at 105 °C to avoid rotting. The dried wastes were ground into smaller pieces (1–2 mm in diameter) and stored inside an air-tight container. The wastes needed to be processed to a smaller size in order to obtain a more accurate result on their thermal decomposition behaviour during the pyrolysis using a thermogravimetric analyser (TGA). A large sample could decrease the efficiency of heat transfer from the surface of sample to its core (Tripathi et al., 2016a), resulting in incomplete pyrolysis of the sample and hence producing inaccurate results from TGA.

2.2. *Analysis of OPW*

Elemental analysis of the wastes were conducted using a FlashEA 1112 CHNS elemental analyzer to quantify the carbon, hydrogen, nitrogen and sulphur contents in the sample, whereas the oxygen content was determined by mass difference (i.e. O = 100 wt% −C–H–N–S) (Liu and Han, 2015). The wastes were dried in an oven at 105 °C to remove any residual moisture content. Next, the fruit wastes were combusted with

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