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Low temperature hydrothermal treatment of palm fiber fuel for simultaneous potassium removal, enhanced oil recovery and biogas production

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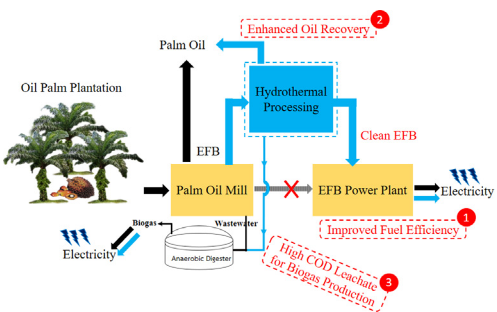
GRAPHICAL ABSTRACT



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ABSTRACT

This work aims to solve the slagging and fouling problems in palm empty fruit bunch (EFB) power plant by means of simultaneous fuel quality improvement and enhanced recovery of EFB fiber oil and biogas from leaching liquid. Rapid accumulation of minerals on heat transfer surfaces has caused the EFB power plants frequent shutdowns for maintenance and considerable thermal efficiency loss. Hydrothermal treatment (HTT) of EFB was performed at low range temperatures (Temp) under various holding times (HT) and biomass-to-liquid ratios (B/L) aiming to improve fuel quality. Removal of potassium (K) was experimentally identified as the key indicator to reduce slagging and fouling indexes (SI and FI) of EFB ash. HTT at 120 °C, 120 min, and B/L 50 g/L gave best K removal at 90.7%, leaving only 0.19 wt% in the fuel, although lesser conditions were also effective. A statistically significant quadratic regression model of K removal was constructed to show the interrelationship among these independent variables. Moreover, it was found that oil recovery from EFB could be enhanced by HTT, gaining an estimate of 221.4 ton/yr of additional oil in a mid-size palm oil mill. The HTT leachate with high organic content is also a potential substrate for methane production in an existing anaerobic digester in the mill. At the end, a practical integration of HTT to palm oil mill with EFB power plant was proposed.

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1. Introduction

For decades, oil palm planting area in the world is continually growing due to versatility of palm oil uses and the amazing efficiency of oil synthesis by palm tree. A number of literatures pointed that palm oil is the most economical oil compared to other bio-oils such as soybean, peanut, sunflower and rapeseed, and its use as ingredient in commodity products, food and feed, already provides great service to our society beside the use as biofuel which helps lessen our great dependency on fossil [1,2]. This truth pushes massive growth of this economic crop and at the same time generates a great amount of palm empty fruit bunch (EFB) as residue. EFB is the most abundant by-product from palm oil mills. In general, 100 tons of palm fresh fruit bunch (FFB) produced about 7 tons of fiber, 20 tons of nut shell, and 25 tons of EFB [3].

Putting it back to palm plantation as humus material would require intensive means of transportation and distribution, leaving alone the enormous stockpiling in plantation since it degrades slowly. It also releases bad odor and greenhouse gases during the decomposition [4,5]. While research on conversion of EFB to bio-chemicals are under, the most practical and economical way to deal with this humongous biomass these days is to thermally convert into energy. Although EFB could be converted biologically, yield of biofuels is still very small due to the recalcitrant nature of the fiber [6]. On the other hand, the presence of high K content, which is known as the major inorganic element in EFB fiber, renders it less effective as a power plant feedstock through the development of slag on surface of water tube and on grate floor in the combustion chamber [7,8]. Fast accumulation of K crust on tube surface hinders heat transfer leading to a worsen fuel economy. Only low-pressure steam can be produced since combustion must be controlled to a lower temperature (< 900 °C) to avoid the melting point of K in ash. Moreover, frequent shutdowns of these EFB power plants for slag removal will lower their readiness to generate electricity, increase maintenance cost, and require great energy to restart the furnace [9].

It is widely known that some abundant minerals and inorganics namely Fe, Ca, Mg, Na, K, Si, Al, and Ti will form their oxide compounds (i.e. Fe_2O_3, CaO, MgO, Na_2O, K_2O, SiO_2, Al_2O_3, TiO_2) during combustion that will eventually develop into slag. These oxides can be used to estimate the tendency to cause problem in boiler in terms of slagging index (SI) and fouling index (FI) [10,11]. SI is an indicator for viscous state of ash deposits (slag) on furnace wall which mainly occurs in the radiant section. Meanwhile, fouling is referred to a dry deposit built by condensed materials occurred mainly on the leading edges of the superheater and reheater tubes in the convection section (after the hot gases exit the furnace). Both indexes indicate deposition tendency on boiler surfaces that obstruct effective heat transfer.

There are several techniques to deal with slagging and fouling problems for trouble biomass; mainly, mineral additive [11,12] and chemical, biological, and thermal pretreatments [5,13]. Nevertheless, only mineral additives and HTT pretreatment are the most promising alternatives to deal with SI and FI. From literatures, four groups of additives are classified; aluminium silicates based (e.g. kaolin), sulfur based (e.g. $Fe_2(SO_4)_3$, $Al_2(SO_4)_3$), phosphorus based (e.g. phosphoric acid), and calcium based (e.g. CaO, $CaCO_3$) [14]. The first three groups target to react with K to form or convert to higher melting temperature complexes, while the last group aims to drive K off from low melting point potassium silicates to flue gas. For instance, kaolin ($Al_2Si_2O_5(OH)_4$ reacts with K containing gases evolved during combustion, forming kalsilite ($KAlSiO_4$) and leucite ($KAlSi_2O_6$) which possess melting points around 1600 and 1500 °C, respectively [12]. Nonetheless, chemical additives could incur other handling and environmental problems, and their addition most certainly lead to higher operation cost [11,15]. Alternatively, biomass pretreatment prior to combustion focuses on the fuel quality improvement, and when optimally applied, can overcome the economic issue related to chemical additive. Reduction of inorganic minerals content in biomass could lower SI and FI in its ash [16].

Hydrothermal treatment (HTT) can be applied for treating different kinds of biomass residues to remove inorganics and produce value-added products such as biochar, high quality pellets and liquid fertilizer [5,16–18]. It was reportedly able to remove K from EFB fiber as high as 74% from HTT [18] and up to 92% when followed by water washing [19] since EFB structural cell will be weakened by high temperature and K ion could dissolve and leache out with water [20]. Besides, improved fuel properties in terms of lower O/C and H/C ratios and higher energy density were attained at temperature 180–220 °C [5]. However, utilization of the leachate as liquid fertilizer added little value to such method. The level of temperature in HTT depends on the objective of research either biochemical extraction, hydrolysis improvement, or sugar conversion [21–23], but minimizing heating energy requirement in doing so has not been aware. Use of temperature at a lower range not only saves energy but also is more practical and, could also preserve the EFB oil property if extracted. At high temperature and its corresponding pressure, special heat resistant vessel is required. Besides, time of biomass under heat treatment and biomass-to-liquid ratio for HTT could influence mineral removal, yet their individual and relative impacts have never been interactively studied. This present work demonstrates the relationship of these critical independent variables for an effective EFB fuel processing. In the end, proper utilization of the extracted oil and HTT liquid could have a great implication for the feasibility and investment of this specific HTT technology for palm oil mill power plant.

Therefore, this research aims to investigate the effects of temperature (Temp), biomass-to-liquid ratio (B/L) and holding time (HT) on improvement of EFB fiber quality by employing low temperature hydrothermal treatment. The main dependent parameters in this work include mineral oxide compounds in ash of EFB under different HTT conditions. The slagging and fouling tendencies in terms of slagging index (SI) and fouling index (FI) were experimentally proven to correlate with K in EFB before the multiple regression analysis on K removal as response was performed. Finally, mass balance of the fiber and potential oil recovery from the proposed low temperature hydrothermal treatment were evaluated based on an upgrading model of a typical palm oil mill power plant.

2. Materials and methods

2.1. Sample collection and preparation

Fresh EFB of species *Elaeis guineensis* was collected from Chumporn Palm Oil Industry in Thasae District, Chumporn Province, Thailand (N10° 50′ 30.0″, E99° 13′ 16.2″). Fig. 1 shows a standard process in palm oil mill which is normally coupled with EFB power plant for electricity generation connected to grid. Assuming negligible solid loss after threshing until screw press, approximately 92 kg (dry basis) per ton of fresh fruit bunch (FFB) is available for EFB power plant since fruit fiber from the palm oil extraction will be used to produce low-pressure steam for use in the mill. The loosened EFB fiber from shredding machine was used in the experiment. This fresh EFB was sampled and analyzed for total solids (TS), volatile solids (VS), and ash content as shown in Table 1. The EFB biomass was then sun dried for 7 days in order to avoid fungus growth, then shredded to 2–5 cm and sieved to remove the over-size and under-size fibers.

2.2. Experimental setup

In this work, a series of batch assays of hydrothermal treatment (HTT) to EFB were performed in order to evaluate the changes in fiber characteristics and the efficiency to reduce slagging index (SI) and fouling index (FI) of EFB ash. This experiment was conducted in full factorial design with variables including biomass-to-liquid ratio (B/L ratio) at 3 levels (50, 75, and 100 g/L), temperature (Temp) at 3 levels (28, 60, and 120 °C), and holding time (HT) at 3 levels (30, 60, and