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Effect of process parameters on hydrothermal liquefaction of oil palm biomass for bio-oil production and its life cycle assessment

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ABSTRACT

This paper presents the studies on the effect of three process parameters; temperature, pressure and reaction time on the subcritical and supercritical hydrothermal liquefaction of oil palm empty fruit bunch, palm mesocarp fiber and palm kernel shell. The effect of temperature (330–390 °C), pressure (25–35 MPa) and reaction time (30–240 min) on bio-oil yields were investigated using a Inconel batch reactor. The optimum liquefaction condition for empty fruit bunch, palm mesocarp fiber and palm kernel shell was at supercritical condition of water; 390 °C and 25 MPa. For the effect of reaction time, bio-oil from empty fruit bunch and palm mesocarp fiber attained maximum yields at 120 min, whereas bio-oil yield from palm kernel shell continued to increase at reaction time of 240 min. Lastly, a life cycle assessment based on a conceptual biomass hydrothermal liquefaction process for bio-oil production was constructed and presented.

1. Introduction

The issue of energy crisis associated with the depletion of fossil fuels reserves and increasing market price of oil and gas has provided strong motivations for the extensive quest for alternative renewable energy sources. Among various alternative renewable energy sources, biomass utilization makes the best attractive option as it can be converted into liquid, solid and gaseous products, from which fuels and fine value-added chemicals can be derived [1]. Besides, biomass utilization is carbon neutral as it does not emit additional greenhouse gases, NO_x and SO_x into the atmosphere [2]. Hence, harnessing the energy stored in the biomass would require energy efficient and cost effective conversion technologies [3].

Depending on the type of products from biomass conversion, there are several thermochemical conversion methods that are commonly utilized to convert biomass to useful products for various applications. Zhang et al. discussed the recent developments and potential applications of thermochemical processes for biomass conversion to bioenergy [4]. Co-combustion of renewable biomass charcoal and diesel slurries as alternative fuels in diesel generating plants was investigated by Soloiu et al. [5]. Torrefaction and carbonization as pre-treatment steps for the production of solid fuels from lignocellulosic biomass was reported by Kambo and Dutta [6]. Chan et al. performed the optimization study of reaction conditions for catalytic pyrolysis of empty fruit bunch for bio-oil production [7]. Apart from that, Demirbas presented a review on the application of supercritical liquefaction process in biorefineries [8]. The effect of catalyst on the co-gasification of rubber seed shell and high density polyethylene for syngas production was investigated by Chin et al. [9]. Among all these technologies, generation of bio-oil from biomass seems to be privileged and advantageous due to the higher energy density output and the ease to transport and store liquid products compared to solid biomass or gaseous products [10].

Biomass-to-liquid (BTL) processes generally include pyrolysis and liquefaction. In pyrolysis, biomass is decomposed and degraded by heat at high temperatures (>400 °C) in the absence of oxygen to produce a mixture of condensable pyrolysis vapor

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(bio-oil), incondensable gases and solid char [11]. However, pyrolysis operations usually require high energy consumption due to the energy-intensive drying process of high-moisture-containing biomass prior to pyrolysis treatment [12]. Compared to pyrolysis, solvolytic liquefaction processes usually operate at milder temperature (<400 °C) and higher pressure (>1 MPa) in the presence of a suitable solvent (water, organic solvent or mixture of water and organic solvent) [13]. In liquefaction, heated and pressurized solvent will break down the complex matrix structure of biomass, producing liquid products that are extracted using organic solvents as bio-oil [14]. The use of solvent in liquefaction processes enables lower process temperatures [15]. Apart from that, the presence of solvent dilutes the concentration of products and prevents formation of tar compounds due to cross-linking and recombination reactions [16].

As water is naturally contained in biomass, liquefaction of biomass for bio-oil production using water (hydrothermal liquefaction) has been widely investigated. Effect of temperature on hydrothermal liquefaction of barley straw was conducted by Zhu et al. [17]. Tungal and Shende [18] studied the effect of catalyst on the hydrothermal liquefaction of pinewood for biogas and biocrude production. The properties of bio-oil produced from hydrothermal liquefaction of microalgae with varying biochemical contents were reported by Biller and Ross [19]. Mazaheri et al. compared the efficiency of catalysts in the subcritical hydrothermal liquefaction of Malaysian oil palm fruit press fiber [20]. The feasibility of liquefying undried macroalgae using water was reported by Yang et al. [21]. The work of Hafez and Hassan had shown the synergetic effect of ethanol in the hydrothermal liquefaction of giant miscanthus [22]. Besides, water is a green and environmentally benign solvent, non-toxic and non-flammable [23]. It is relatively cheap and abundant, and hence safe to be employed in larger bio-oil production scale [24]. In this study, water in subcritical and supercritical conditions is used as a solvent to liquefy oil palm biomass. Subcritical water is water below the critical temperature (374 °C) and above the vapor pressure at that temperature, whereas supercritical water is water above the critical temperature (374 °C) and critical pressure (22.1 MPa) [25]. Due to the low dielectric constant, weak hydrogen bond and high isothermal compressibility of subcritical water, it is suitable to be used to degrade and decompose biomass into gaseous, liquid and solid products [20]. Supercritical water possesses liquid-like densities and gas-like high compressibilities and diffusivities, making supercritical water a powerful solvent in the extraction, degradation and separation of organic compounds [26].

Oil palm (*Elaeis guianensis*) is the major industrial crops in Malaysia, producing 40–60% of total oil palm in the world for the past 25 years [15]. As a result of large scale of oil palm plantations in Malaysia, staggering amounts of oil palm biomass wastes (~86.9 Mt/year as in 2010), are produced [27]. These wastes can be utilized in the generation of bio-oil. In this work, the effect of temperature, pressure and reaction time on the bio-oil yield from hydrothermal liquefaction of empty fruit bunch (EFB), palm mesocarp fiber (PMF) and palm kernel shell (PKS) is investigated.

In addition, a life cycle assessment (LCA) based on a conceptual biomass liquefaction process is also conducted and presented. Life cycle assessment is a systematic method used to evaluate the environmental impacts of a technological system throughout its life cycle [28]. It has been employed in a wide range of applications. For example, Cherubini and Ulgiati compared the LCA of a biorefinery concept generating bioethanol, bioenergy and biochemicals from corn stover and wheat straw [29]. Woon and Lo performed LCA on the analysis of environmental hotspots of proposed landfill extension and advanced incineration facility [30]. Amor et al. integrated electricity supply dynamics to refine the LCA results on a renewable distributed generation system [31]. Ng et al. performed LCA to examine the impacts of different domestic wastewater streams and the effectiveness of two water conservation policies [32]. However, to the authors' best knowledge, the environmental impacts of bio-oil production from biomass via hydrothermal liquefaction have not been widely reported in the literature, although there are LCAs reporting the comparisons between several choices of conversion technologies. LCA of eight types of advanced thermal technologies utilizing pyrolysis and gasification for waste treatment were conducted by Khoo [33]. Meanwhile, the LCA of biofuel production from corn stover fast pyrolysis and subsequent hydroprocessing and upgrading process was reported by Dang et al. [34]. Liu et al. [35] and Fortier et al. [36] conducted LCA studies related to the hydrothermal liquefaction process of algae and microalgae, for biofuels and bio-jet fuel production, respectively. Due to the limited LCA study on the hydrothermal liquefaction of lignocellulosic biomass for bio-oil production reported, it is vital to conduct a LCA study to gain preliminary insights into the environmental impacts associated with the conceptual process of oil palm biomass liquefaction for bio-oil production.

2. Materials and methods

2.1. Feedstock pre-treatment and characterization

Raw empty fruit bunch (EFB), palm mesocarp fiber (PMF) and palm kernel shell (PKS) were supplied by FELCRA Nasaruddin Oil Palm Mill, Bota, Perak, Malaysia. These biomass feedstocks were first washed with water thoroughly to remove impurities and sand particles, then manually chopped into smaller pieces and dried in the oven at 80 °C for 48 h, before being grinded with a FRITSCH Cutting Mill and sieved to particle size of <710 μm before being used as feedstocks in the experiments.

EFB, PMF and PKS were characterized for their structural and elemental compositions and higher heating values (HHV). For structural analysis, biomass samples were sent to Forest Research Institute Malaysia (FRIM) for analysis of hemicellulose, cellulose and lignin content, while the remaining components were assumed to be extractives and ash, as reported in the literature pertaining to characterization of nine types of lignocellulosic biomass [37]. Similar characterization manner for structural content of oil palm biomass wastes was also reported by Kelly-Yong et al. [38]. Elemental compositions and higher heating values were determined using a LECO 932 CHNS Analyzer and IKA C5000 Bomb Calorimeter, respectively. Table 1 shows the properties of the oil palm biomass used in this work.

Table 1
Properties of oil palm biomass (dry basis).

Biomass	Structural analysis (%)				Ultimate analysis (%)					Higher heating value (MJ/kg)
	Hemicellulose	Cellulose	Lignin	Extractives and ash[a]	C	H	N	S	O[a]	
EFB	26.9	26.6	18.6	27.9	43.62	4.03	1.96	0.17	50.22	16.3
PMF	22.2	23.1	30.6	24.1	46.29	4.67	1.42	0.24	47.37	16.5
PKS	22.9	24.5	33.5	19.1	47.77	4.06	0.46	0.16	47.55	17.5

[a] Calculated by difference.