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Review

Torrefaction of microalgal biochar as potential coal fuel and application as bio-adsorbent

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ABSTRACT

Microalgal biomass is the third-generation promising feedstock for production of biofuel and other valuable goods. The raw microalgal biomass and residues have low calorific value, high moisture, and high H/C and O/C atomic ratio which not suitable to use as solid fuel and many engineering applications. Torrefaction is a promising technique to upgrade microalgal biomass closed to solid coal properties by increasing the calorific value of microalgal biochar. However, the overview of torrefaction process for microalgal biochar is lacking in the literature study. Thus, an overview of recent dry and wet torrefaction of microalgal biomass is presented in this review. Wet torrefaction is a new technology for microalgal biochar production because it has some advantages compare with other pre-treatment methods. Besides, this review aims to provide a comprehensive overview of recent research for fuel property of microalgal biochar after torrefaction process. Different torrefaction temperature, gases and holding time lead to various solid yield, energy yield and calorific value of biochar are comprehensively discussed. In addition, the used of microalgal biochar as bio-adsorbent to remove pollutants in wastewater are included as well. In short, this is a comprehensive summary of recent torrefaction technology for microalgal biochar as fuel.

1. Introduction

The increasing population in global and living standards has risen the consumption of global energy recently. The usage of fossil fuel emits vast volume of greenhouse gases and consequently contributed to severe environmental pollution. Besides, fossil fuel as a non-renewable energy is facing supply shortage in coming years [1]. To overcome these problems, many researchers developed renewable energy and alternative sources to replace shortage of fossil fuel. Biomass energy is proven to have a clean combustion compared to fossil fuel and has potential to reduce the emission of greenhouse gases to atmosphere [2].

Microalgal biomass is known as the third generation biofuel source and a potential resource for bioenergy industry due to fast growing organism [3]. Microalgal biomass is rich in nutritional contents such as carbohydrates, proteins, and lipids that are used for biofuels [4], foods [5], soil additives [6], livestock feeds [7], pigments [8], nutraceuticals [9], cosmetics [10] and so on. Microalgal biomass after extraction has low heating value, high moisture and ash content, and hygroscopic nature. Direct combustion of microalgal biomass will contribute to greenhouse gases that will pollute the environment. The environmental pollution problems can be solved by converting biomass into biochar [11]. Biochar is a char with carbon-rich material from a biomass which is produced by thermal decomposition of organic feedstock without oxygen supply [11]. Biochar has many advantages in applications such as soil fertility improvement, carbon sequestration, adsorbent, and agricultural by-product recycling. This creates the interest of multi-disciplinary areas for science and engineering for the application of biochar [12].

Pyrolysis of biomass is one of the promising techniques for biofuel production in the form of char, oil and gas. Fig. 1 shows production of microalgal biochar via pyrolysis and torrefaction. High surface area of microalgal biochar produced by pyrolysis is suitable to use as bio-adsorbent for removing the contaminant in aqueous solution. Pyrolysis can produce biochar as solid fuel, but the increased in calorific value of biochar is lower than torrefaction process. High quality of solid fuel can be obtained from torrefaction of biomass compare to pyrolysis [13].

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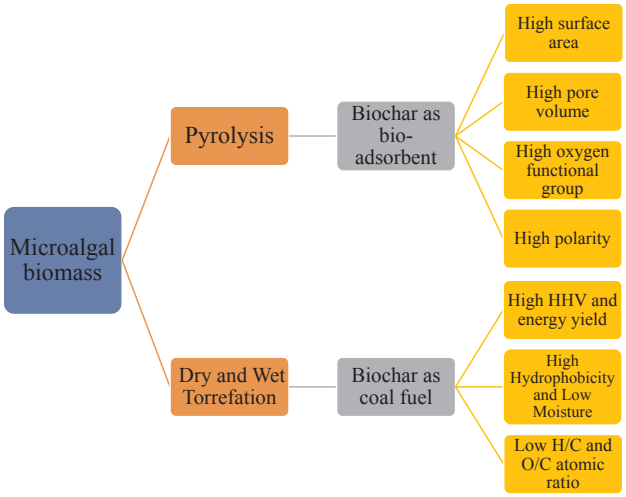

Fig. 1. Microalgal biochar as bio-adsorbent and coal fuel.

Torrefaction is a thermochemical conversion technique for production of coal fuel from biomass [14]. The research of torrefaction of biomass has increased drastically to upgrade biomass as solid fuel coal that can partly replace fossil fuel in industry [13,15]. Torrefied biomass gives higher heating value and carbon content, better grindability and hydrophobic, and low atomic ratio, ash and moisture content compared to raw biomass [1,16]. Torrefaction changes biomass properties and increases energy quality of biomass quality, making it more practical and suitable to be use as coal fuel. The milder treatment condition of torrefaction gives higher solid mass yield and productivity compared to conventional pyrolysis with higher temperature [17].

Microalgal biochar produced via pyrolysis can be used as adsorbent for removal of heavy metal, organic and inorganic contaminants from wastewater and soils [18,19]. The selection of better properties biomass as bio-adsorbent is an important factor to reduce the pollutants present in wastewater [20]. Wastewaters are severely polluted that will consequently leads to environmental problems due to the high chemical oxygen demand (COD) and biological oxygen demand (BOD), and rich in organic and inorganic nutrients [21]. Microalgae can be used as absorbent during cultivation stage and after converting into biochar. Cultivation of microalgae adsorbs the nutrients and metals contained in wastewater to improve wastewater quality and sustainability [22]. Microalgae reduces large amount of carbon dioxide because microalgae biomass required carbon dioxide to cultivate. Microalgae consists of high carbon fixing or photosynthetic efficiency compared to plants at lands to allow low-cost efficiency carbon mitigation [23,24]. Conversion of microalgal biomass to biochar stores the carbon dioxide in the form of solid to mitigate carbon to atmosphere [25]. Production of microalgal biochar efficiently mitigates the carbon and adsorb contaminant from cultivation stage to biochar production process.

In this study, production process of microalgal biochar such as pyrolysis, hydrothermal carbonization and torrefaction are reviewed. This review aims to summarize and discuss the torrefaction process of microalgae biomass such as dry torrefaction and wet torrefaction. The fuel characteristics of torrefied microalgal biochar from previous studies are analysed for the used as coal fuel. Lastly, the application of microalgal biochar as bio-adsorbent is reviewed.

2. Microalgal biochar production and development

Biochar can be produced by thermochemical conversion of biomass such as pyrolysis, hydrothermal carbonization and torrefaction that is more popular compared to biochemical conversion that gives low yield in biochar [26,27]. Through thermochemical conversion processes of microalgal biomass, heat and power can generate in the form of biochar, bio-oil and gas [28]. Biochar produced can be used as power generation, carbon sequester [29], soil amendment to improve soil quality or fertilizer [30], and adsorbent for pollutants [18]. The bio-oil produced has high energy content and is suitable for generating power. It is comparable to fossil fuel after convert to biofuel [31]. Besides, gaseous form such as syngas produced by thermochemical conversion of microalgae is suited for the production of biofuel [32]. This review is more concerned on the techniques of production of microalgal biochar and focused on characteristic and properties of microalgal biomass undergoing torrefaction process.

Pyrolysis is one of the conversion technique by heating the raw biomass at high temperature and inert condition [27]. Today, slow pyrolysis [33] and microwave-assisted pyrolysis [34] are pyrolysis techniques to convert biomass into high yield of biochar. Slow pyrolysis is known as carbonization where production of char is the main goal. It is one of the oldest process of pyrolysis of biomass, by heating biomass at low temperature (~400 °C) for a long period, more than one hour to several days to increase the formation of char [35]. Microwave-assisted pyrolysis heats the inner of biomass directly by penetrating the wall of the container [34], where conventional pyrolysis will first heats the wall of container and thereafter heats the biomass. Microwave heating is found to have higher biochar yield than conventional heating [36], while the increasing of microwave heating power decreases the biochar yield of microalgae [37].

Hydrothermal carbonization is the heating of biomass in water at subcritical with temperature (180–250 °C) and self-produced pressure up to 2 MPa to produce hydrochar as main output. Water acts as catalyst, medium and reactant during the carbonization process. The end products of the hydrothermal carbonization are in the form of solid (hydrochar), liquid (bio-oil) and gases with the properties depend on the biomass feedstock. Biomass with high moisture content is suitable to use hydrothermal carbonization compare to dry carbonization [38]. Hydrothermal carbonization dehydrated water content of biomass using pressure by saving time and energy to dry the biomass. Fuel properties of the biomass can be improved through this process and the hydrochar produced can be used as fertilizer to improve the soil properties [39]. Therefore, hydrothermal carbonization has been widely used to improve the physical and chemical properties of wet biomass for the agriculture application [40,41].

Torrefaction can be divided into dry torrefaction and wet torrefaction. Dry torrefaction converts raw biomass into biochar by heating at temperature between 200 °C and 300 °C, under atmospheric pressure and inert nitrogen with absent of oxygen. Hydroxyl groups of the biomass are removed during torrefaction and producing hydrophobic groups. The major benefits of torrefied biomass are increased in higher heating value, energy density and carbon content while decreased in atomic ratio and moisture content compared to raw biomass [16]. The solid coal fuel is the main product during the torrefaction, will liquids and gases produced as side-products [42]. Wet torrefaction used lower temperature and residences time to produce high energy dense biochar compared to dry torrefaction. Sub-critical water is used as reaction medium for wet torrefaction. The disadvantages of using wet torrefaction is high cost for setup and maintenance due to high pressure during the torrefaction process [43].

2.1. Dry torrefaction

Dry torrefaction, or in another word mild pyrolysis or low temperature pyrolysis. Torrefaction is a process to improve the characteristic of biochar closed to coal fuel. The process destroys the structure of the biomass but also upgraded the biomass calorific value and energy density [13]. The general process of dry torrefaction is shown in Fig. 2 [44] and the literature survey of torrefaction of microalgae and others biomass is shown in Table 1. The torrefaction of biomass can be classify into light, mild and severe torrefaction with temperature around 200 to 235 °C, 235 to 275 °C and 275 to 300 °C. This significantly affects the