An energy analysis of torrefaction for upgrading microalga residue as a solid fuel

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HIGHLIGHTS

- Energy utilization of microalga residue torrefaction is analyzed by examining contour maps.
- Optimal operation can be found to maximize the heating value of biomass and minimize solid yield.
- Relative energy efficiency (REE) is defined to identify the performance of energy utilization.
- The maximum REE along the contour line of energy yield always occurs at 300 °C.
- The energy efficiency under a given energy yield can be enlarged by a factor of at least 2.13.

GRAPHICAL ABSTRACT
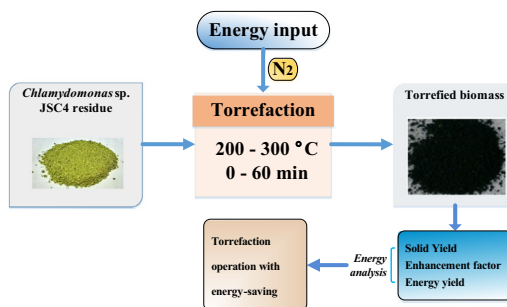
ABSTRACT

The torrefaction characteristics and energy utilization of microalga *Chlamydomonas* sp. JSC4 (*C.* sp. JSC4) residue under the combination of temperature and duration are studied by examining contour maps. The torrefaction temperature on the contour line of solid yield has a trend to linearly decrease with increasing duration. An index of relative energy efficiency (REE) is introduced to identify the performance of energy utilization for upgrading biomass. For a fixed energy yield, the optimal operation can be found to maximize the heating value of the biomass and minimize the solid yield. The energy utilization under the combination of a high temperature and a short duration is more efficient than that of a low temperature and a long duration. The maximum REE along the contour line of energy yield is always exhibited at the highest temperature (300 °C) where the energy efficiency can be enlarged by a factor of at least 2.36.

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1. Introduction

Thermal degradation of biomass in an elevated-temperature environment plays an important role in biofuel production and bioenergy development. Depending on the reaction temperature, oxidizer concentration, and pressure, the commonly utilized techniques for bioenergy through the thermal degradation include combustion, gasification, pyrolysis, and torrefaction (Chen et al., 2015a). Biomass can be burned in a sufficient oxygen environment and the prime product is heat. Biomass gasification is performed in an oxygen-starved atmosphere and the main product is syngas,

namely, $H_2 + CO$. In an inert or oxygen-free environment, liquid fuels or bio-oils can be produced from the fast pyrolysis of biomass, whereas solid fuels can be produced from slow pyrolysis and torrefaction. In recent years, torrefaction has attracted a great deal of attention for solid fuel production (Tapasvi et al., 2012; Peng et al., 2013; Du et al., 2014). This arises from the fact that torrefaction at temperatures of 200–300 °C can effectively improve biomass properties; the advantages include reducing moisture and microbial degradation, converting hygroscopic biomass into hydrophobic material, intensifying calorific value, increasing grindability, and enhancing biomass uniformity (Chen et al., 2012; Tran et al., 2013; Lu et al., 2013; Basu et al., 2014).

When biomass serves as a feedstock for biofuel production, algal biomass is considered as a promising raw material because the biomass distributes widely and grows rapidly (Brennana and Owende, 2010). Algal biomass is high-efficiency photosynthetic microorganisms that can convert sunlight, water, and CO_2 into cells, implying that atmospheric CO_2 becomes the carbon source in cells. Therefore, carbon fixation is implemented when algal biomass is cultivated and harvested (Chen et al., 2014b). On account of the aforementioned merits, many studies have been performed on biofuel production from algal biomass. Algal biomass derived biofuels are termed third-generation biofuels (Ahmad et al., 2011; Nigam and Singh, 2011; Chen et al., 2015a). Microalgae pertain to algal biomass in which proteins, lipids, and carbohydrates are the main substituents. By extracting oils in microalgae followed by the transesterification process, biodiesel is produced (Johnson and Wen, 2009). Bio-butanol and bioethanol can be produced from the fermentation of carbohydrates in microalgae (Ellis et al., 2012; Jang et al., 2012). Alternatively, gaseous biofuels, such as methane and bio-hydrogen, can also be produced from the fermentation and the photobiological process of microalgae (Brennana and Owende, 2010). After the aforementioned biofuels are produced, residual solids become wastes. These microalgae wastes can be burned directly. However, the calorific values of the residues are relatively low; they are inappropriate to be used as fuels in industry (Chen et al., 2014a). In this aspect, torrefaction can be employed to upgrade the wastes and improve their calorific values. This makes the HHV of torrefied biomass approaches that of coal.

When biomass undergoes torrefaction, temperature and duration are the two most important factors affecting the upgrade performance (Chen et al., 2015b). On the other hand, a few studies (Rousset et al., 2012; Lu et al., 2012; Uemura et al., 2013; Wang et al., 2013) focused on biomass torrefaction in an oxidative environment, using air rather than nitrogen as a carrier gas to reduce the operating cost. The energy yield, which is the ratio of energy amount between torrefied biomass and its parent biomass (Park et al., 2012), is the most crucial index to identify torrefaction performance. Alternatively, the enhancement factor of higher heating value (HHV), which is the ratio of HHV between upgraded biomass and its raw counterpart (Chen et al., 2015b), can be thought of an indicator of torrefaction quality. Specifically, the higher the enhancement factor, the better the torrefaction quality. A high torrefaction temperature along with a long duration leads to a high enhancement factor, but this results in a low solid yield (Li et al., 2012).

Biomass with high calorific value is always desired for its application in industry, and can be achieved by means of torrefaction with high severity. However, a high torrefaction severity suffers from the penalty of a low solid yield (Medic et al., 2012). The increase in the enhancement factor cannot keep up with the decrease in the solid yield. As a result, increasing torrefaction severity lowers the energy yield all the time. Consequently, a compromise between energy (or HHV) densification and solid yield reduction may be required for getting a feasible energy yield. This inspires the objective of the present study to simultaneously enhance the calorific value of biomass and avoid the obvious weight loss of biomass from torrefaction. Many studies had paid to the HHV, solid yield, and energy yield of torrefied biomass, but less focus fell on the combination of torrefaction temperature and duration for reaching a desired energy yield, especially in microalgae residues. This study is intended to analyze the efficiency of energy input for biomass torrefaction under the goal of a desired energy yield, from the operating point of view. The obtained results are able to provide a practical insight into the operation of torrefaction for upgrading biomass or microalgae residues as fuels employed in industry.

2. Experimental

2.1. Preparation and properties of material

The solid residue of microalga *Chlamydomonas* sp. JSC4 (*C.* sp. JSC4) undergoing oil-extraction was adopted as the raw material of torrefaction. The microalga *C.* sp. JSC4 was an oil-rich biomass which was isolated from freshwater in southern Taiwan (Nakanishi et al., 2014). The residue was first dried in an oven at 85 °C for 10 h to eliminate its surface water. Then, the dehydrated residue was comminuted by a shredder and sieved by a 40-mesh screen. This yielded the treated particle sizes less than 0.42 mm. The powders were collected in sealed plastic bags and stored in a desiccator at room temperature until torrefaction experiments were carried out.

The experimental system for biomass torrefaction was made up of a steel cylinder, a flow rate controller, and a reactor. Nitrogen (99.99 vol%) stored in the steel cylinder was used as the carrier gas to provide an inert or oxygen-free environment in the course of torrefaction. The volumetric flow rate of nitrogen was controlled by a mass flow meter (Brooks 5850E) which was connected with a readout device (KD-4000). The reactor comprised a glass tube, a tube furnace, and a power controller. Tested samples were placed in the tube which was situated in the furnace. A temperature probe (K-type thermocouple) was embedded in the furnace by the glass tube to measure the torrefaction temperature and provide a

Table 1
A list of basic properties of microalga *C.* sp. JSC4 and its residue after oil extraction.

Biomass	*C.* sp. JSC4	*C.* sp. JSC4 residue
Photograph		
Composition analysis (wt%)		
Crude protein	5.15	6.56
Crude lipid	10.93	1.95
Carbohydrate	34.41	41.39
Others	49.51	50.10
Proximate analysis (wt%)		
Volatile matter (VM)	79.88	71.27
Fixed carbon (FC)	8.05	12.57
Moisture	6.31	8.34
Ash	5.76	7.82
Elemental analysis (wt%, dry-ash-free)		
C	50.59	48.06
H	8.12	7.62
N	2.60	3.81
O (by difference)	38.69	40.51
Chemical formula	$CH_{1.92}O_{0.57}N_{0.04}$	$CH_{1.90}O_{0.68}N_{0.06}$
HHV (MJ kg^{-1})[*]	19.27	16.91

[*] Dry basis.