



# Torrefaction operation and optimization of microalga residue for energy densification and utilization



Wei-Hsin Chen<sup>a,\*</sup>, Ming-Yueh Huang<sup>a</sup>, Jo-Shu Chang<sup>b,c</sup>, Chun-Yen Chen<sup>d</sup>

<sup>a</sup> Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan

<sup>b</sup> Department of Chemical Engineering, National Cheng Kung University, Tainan 701, Taiwan

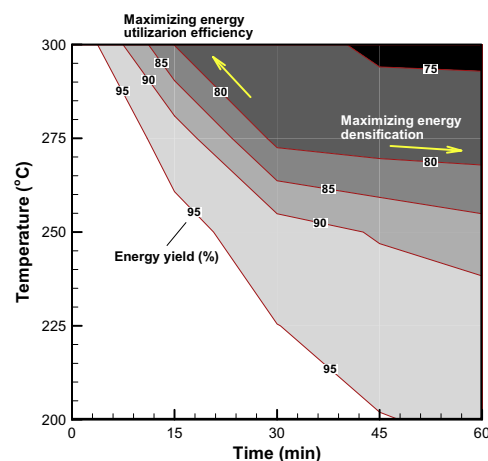
<sup>c</sup> Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan 701, Taiwan

<sup>d</sup> Center for Bioscience and Biotechnology, National Cheng Kung University, Tainan 701, Taiwan

## HIGHLIGHTS

- A microalga residue torrefied in N<sub>2</sub> and CO<sub>2</sub> is studied.
- Torrefaction severity index can be employed to predict the properties of the upgraded biomass.
- The solid and energy yields of the biomass torrefied in CO<sub>2</sub> are lower than in N<sub>2</sub>.
- The best torrefaction quality at a fixed energy yield can be obtained by maximizing duration.
- The higher the torrefaction temperature, the higher the energy utilization for biomass upgrade.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The torrefaction characteristics of a microalga (*Chlorella vulgaris* ESP-31) residue in inert (N<sub>2</sub>) and non-inert (CO<sub>2</sub>) atmospheres at temperatures of 200–300 °C with the durations of 15–60 min are investigated. A parameter of torrefaction severity index (TSI) is employed to account for the thermal degradation phenomena. The results indicate that the enhancement factor of higher heating value, energy yield, and atomic H/C and O/C ratios versus TSI are strongly characterized by a linear relationship. The solid and energy yields of the residue torrefied in CO<sub>2</sub> are lower than in N<sub>2</sub> inasmuch as the thermal degradation in the former is more active, presumably due to the intensified reaction of CO<sub>2</sub> with volatile matters in the biomass. At a given energy yield, the microalga residue torrefied at a lower temperature accompanied by a longer duration results in a fuel with higher energy densification and lower solid yield, thereby rendering the better torrefaction quality. On the other hand, a higher efficiency of energy utilization for upgrading the biomass can be achieved at a higher temperature along with a shorter duration. It is thus concluded that the optimization of torrefaction operation depends on the requirement of energy densification or energy utilization on fuel.

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\* Corresponding author. Tel.: +886 6 2004456; fax: +886 6 2389940.

E-mail address: [weihsinchen@gmail.com](mailto:weihsinchen@gmail.com) (W.-H. Chen).

## 1. Introduction

In recent years, the interest in the study of torrefaction is growing drastically [1]. This arises from the fact that torrefaction is an effective route to upgrade biomass for producing solid carbon-neutral fuels. Torrefied biomass can partly replace fossil fuels utilized in industry [2–4], thereby abating CO<sub>2</sub> emissions and mitigating atmospheric greenhouse effect. Recent studies have addressed that the properties of biomass, such as moisture content, calorific value, grindability, biodegradation, lignocellulosic uniformity, and hygroscopic nature, are altered significantly from torrefaction [5–7]. These changes are attributed to the thermal degradation of biomass so that the lignocellulosic constituents, structures, and functional groups vary permanently.

On account of the improved properties of biomass from torrefaction, the applications of torrefied biomass in industry, such as co-firing, ironmaking, and gasification, have received a great deal of attention. The study the co-firing of torrefied biomass and pulverized coal in boilers [3] illustrated that torrefaction was able to provide a technical option for high substitution ratios of biomass in the co-firing system, and 100% of torrefied biomass could even be fired in the pulverized coal boiler. The evaluation of the potential of torrefied biomass injected into blast furnaces for ironmaking [4,8] indicated that the torrefaction temperature of 300 °C was a feasible temperature to transform biomass into solid fuel resembling a high-volatile bituminous coal consumed for blast furnaces. For the utilization of torrefied biomass in gasification, the experimental [9], numerical [10] and thermodynamic [11] studies revealed that the syngas yield, syngas quality, and cold gas efficiency from the gasification of torrefied biomass were better than those of raw biomass. Meanwhile, the numerical analysis by the Taguchi approach [12] suggested that torrefaction was an important factor in determining the performance of co-gasification of biomass and coal.

Depending on the processing medium, as a whole, the torrefaction technology can be classified into dry and wet torrefaction [1,13,14]. When one is concerned with dry torrefaction, it can further be divided into non-oxidative and oxidative torrefaction. In non-oxidative torrefaction, biomass is conventionally torrefied in an oxygen-free environment to avoid oxidative reactions, and nitrogen is the most commonly used medium [15]. Using CO<sub>2</sub> as a carrier gas in torrefaction has also been carried out to achieve the utilization of the greenhouse gas from industry [16,17]. Biomass torrefied in CO<sub>2</sub> is more active than in nitrogen [16,17], revealing that CO<sub>2</sub> is not an inert medium in biomass torrefaction [16]. As long as oxygen is contained in carrier gas, oxidative reactions in the upgrading process occur, yielding the oxidative torrefaction [18–23]. Overall, the solid yield from biomass torrefaction in air is lower than in nitrogen [19], and an increase in the superficial velocity of air leads to a higher weight loss of biomass [20]. Increasing the O<sub>2</sub> concentration in the carrier gas with a higher torrefaction temperature also leads to a higher weight loss [18,21,23].

After biomass is torrefied, the solid yield, the enhancement factor of higher heating value, and the energy yield are three important indicators to evaluate the performance of torrefaction. The higher the solid yield, the higher the energy yield is [1,24,25]. However, the densification in the calorific value of biomass from torrefaction is insignificant so that the torrefied biomass cannot be adopted as a substitute to coal used in industry. It has been shown that there is a strong correlation between the energy yield and the solid yield [1], that is, the energy yield linearly decreases with the decreases of solid yield. Accordingly, a balance between appropriately enhancing the heating value of biomass and reducing the solid yield is required. To identify the torrefaction degree of biomass, a parameter of torrefaction severity index (TSI), in


terms of the weight loss ratio between a certain operation and a reference operation, has been defined [26].

Microalgae have been thought of as a crucial feedstock for the production of third-generation biofuels, such as bioethanol, bio-butanol, biodiesel, and bio-oils [27]. After the biofuels are produced from microalgae, their residues become wastes. Torrefaction is a potential way to upgrade the residues to generate solid fuels, thereby accomplishing the secondary energy recovery from microalgae. Reviewing literature suggests that only a few studies were performed on the torrefaction of microalgae or microalgae residues for solid fuel production [26,28,29]. In particular, the information concerning energy analysis from the perspectives of energy densification and utilization remains insufficient. To provide a deep insight into the torrefaction of a microalga residue, the present study aims to: (1) investigate the properties of the microalga residue torrefied in N<sub>2</sub> and CO<sub>2</sub>, (2) analyze the relationship between the torrefaction characteristics and severity, and (3) figure out the energy densification and utilization for torrefaction operation. The obtained results are able to provide useful insights into the operation for upgrading microalgae residues via torrefaction.

## 2. Material and experimental procedure

The feedstock used for the torrefaction experiments was the oil-extracted residue of microalga *Chlorella vulgaris* ESP-31 (*C. vulgaris* ESP-31), which is a freshwater microalga isolated from a shrimp pond located in southern Taiwan [30]. The *C. vulgaris* ESP-31 strain was grown outdoors in a 50 liter vertical tubular photobioreactor and the freshly harvested microalgal biomass after nearly 10-day cultivation contained a lipid content of 35–44 wt% [31], depending on the weather conditions while it was grown. The ESP-31 strain could accumulate over 50 wt% lipid content when it was cultivated indoors under optimum conditions [32,33]. Nearly 90% of lipids in the microalgal biomass were extracted by using a hexane/methanol co-solvent system as the oil content of the microalgae residue dropped to less than 4% (Table 1). The extracted microalgal oil mainly consists of palmitic acid (C16:0), stearic acid (C18:0) and oleic acid (C18:1), thus being suitable for biodiesel production [32,33]. In this study, the

**Table 1**  
Basic properties of *C. vulgaris* ESP-31 residue.

Biomass	<i>Chlorella vulgaris</i> ESP-31 residue
Photograph	
<i>Composition analysis (wt%, dry-ash-free)</i>	
Crude protein	7.45
Crude lipid	3.81
Carbohydrate	38.74
Others	50.0
<i>Proximate analysis (wt%)</i>	
Volatile matter (VM)	72.31
Fixed carbon (FC)	14.17
Moisture	3.75
Ash	9.77
<i>Elemental analysis (wt%, dry-ash-free)</i>	
C	47.78
H	7.85
N	4.14
O (by difference)	40.23
Chemical formula	CH <sub>1.97</sub> O <sub>0.63</sub> N <sub>0.07</sub>
HHV (MJ kg <sup>-1</sup> , dry basis)	17.90

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