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# LIFE CYCLE ASSESSMENT OF TORREFIED MICROALGAE BIOCHAR USING TORREFACTION SEVERITY INDEX

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## ABSTRACT

Microalgae biomass is composed of various bio-compounds which can be converted to biofuels. One type of solid fuel which can be derived from microalgae is biochar through torrefaction. However, the production of torrefied microalgae biochar may include environmental impact as it consumes raw materials and energy. A life cycle assessment of the production of torrefied microalgae biochar is proposed in the study using the torrefaction severity index. The results show the electricity requirement of the torrefaction largely contributes to the environmental impact and energy consumption. While the resulting global warming potential of the production of torrefied microalgae biochar using the torrefaction severity index yielded a non-linear relation.

**Keywords:** life cycle assessment, torrefaction, microalgae, biochar

## NOMENCLATURE

| | |
|---|---|
| CML | Cumulative energy demand |
| FEP | Freshwater eutrophication potential |
| GWP | Global warming potential |
| LCA | Life cycle assessment |
| MEP | Marine eutrophication potential |
| PMP | Particulate matter potential |
| TAP | Terrestrial acidification potential |

## 1. INTRODUCTION

Third generation biomass feedstock, such as microalgae biomass, arises from the concerns associated in the first and second-generation biomass feedstock. The growing concern involves the fossil versus fuel debate and larger land area for cultivation. Microalgae is a unicellular microorganism that is typically found in freshwater and has the characteristics of having high photosynthetic efficiency, and fast growth rate [1].

Biochar, bio-oil, and syngas can be produced from microalgae biomass through thermochemical conversion processes. For the utilization of solid fuel, one promising technology is through torrefaction. Torrefaction is a thermochemical pretreatment process for upgrading biomass to higher quality and better form of biofuel. It is performed in an inert environment of one atmospheric pressure, at the temperature range of 200-300 °C, and the duration of 10-90 minutes[1]. After torrefaction, the microalgae biochar heating value is 25 MJ $kg^{-1}$ which is at par with coal having a range from 25 to 35 MJ $kg^{-1}$ [2].

However, any biofuel production entails different degrees of environmental problems and energy consumption. Therefore, previous life cycle assessment (LCA) studies were performed on torrefied lignocellulosic biomass such as olive-husk[3], rice-straw[4], and wood[5]. To date, only the works of [6, 7] have focused on the LCA study of torrefied microalgae biomass. However, the scope of these two studies considered a cradle to bioenergy product scope and have not included the influence of the torrefaction severity index (TSI). TSI is an important performance indicator used to measure solid weight loss during the biomass conversion to solid fuel. The significance of including the TSI in the LCA enhances the resolution of the analysis by determining the influence of torrefaction parameters such as temperature and duration in the LCA study.

To address this research gap, the study focuses on developing a cradle to grave LCA of the torrefied microalgae biochar using the torrefaction severity index.

Furthermore, a comparison between a lab-scale and a pilot-scale scale torrefied biochar production is also considered in the analysis.

## 2. METHODOLOGY

### *2.1. Material preparation*

The indigenous microalga *Chlorella Vulgaris* FSP-E is obtained from the Research Center for Energy Technology and Strategy Laboratory, National Cheng Kung University, Tainan, Taiwan. The microalga is cultured in a glass photobioreactor using an artificial light source, continuous supply of $CO_2$, and 300 rpm agitation rate. The biomass is harvested by centrifugation and undergone freeze-drying. The dried biomass is transferred at the Green Energy and Fuel Laboratory for torrefaction experimentation. It is first dried in the oven for 24 hours to remove extra moisture and sieved and grind at <3mm particle size. The powders are collected and stored in a desiccant room until torrefaction experimentation is carried out.

### *2.2. Microalgal biochar production using torrefaction*

The torrefaction experimentation is performed using a reactor, steel cylinder, flow rate controller, and a circulating cooling bath. Pure nitrogen (99.99%), fixed at 100 ml/min, is used to provide the inert environment. The reactor is composed of a glass tube, power controller, and a tube furnace. For temperature measurement, an embedded K-type thermocouple was used.

### *2.3. Torrefaction severity index (TSI)*

Torrefaction severity index (TSI) is defined as the ratio of the biomass' weight loss at the torrefaction condition to the weight loss at the maximum condition (see Eq. 1). The TSI value is between 0 and 1, where a value of 0 indicates no weight loss has occurred. The TSI value of 1 is set for the microalgae severe torrefaction condition occurring at 300 °C and a duration of 60 minutes. The highest weight loss for *C. vulgaris* is 47% [8].

From the contour map of *C. vulgaris,* as shown in Fig 2, the gradient at the highest temperature of 300 °C shows a larger influence over the residence time along with the 60 minutes duration. This indicates that the torrefaction temperature has a significant impact over the torrefaction duration in terms of solid yield [8].

$$TSI = \frac{WL_{T,t}}{WL_{300°C,60\ min}} \qquad (1)$$

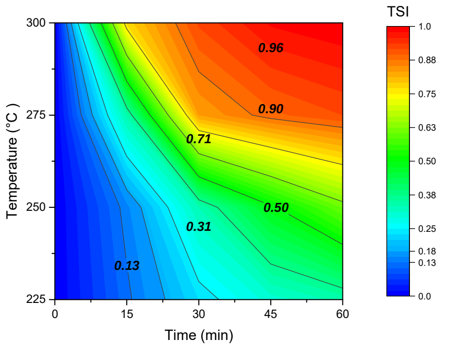


Fig 1 Contour map of torrefaction severity index (TSI)

### *2.4. Life Cycle Assessment (LCA)*

Life cycle assessment (LCA) is a scientific tool used to evaluate the potential environmental impact and energy consumption based on all the stages of the product's life, activities, or processes. To provide a comprehensive analysis, the LCA of microalgae bio-char production is carried out using a commercially available LCA tool SimaPro v8.5.2 develop by Pre-consultants. The ReCiPe Midpoint (H) V1.02 impact assessment and Cumulative Energy Demand (CED) V1.10 methodology by Ecoinvent are used to characterized the total life cycle environmental impact potential and analyzed the energy consumption in accordance to the input and output of the energy and material flow, respectively. The functional unit used is 1 kg torrefied microalgae biomass and the system boundary from cradle-to-grave.

#### *2.4.1. Life cycle inventory*

The life cycle inventory involves the microalgae cultivation, harvesting, drying, torrefaction process, and biochar usage as a soil amendment. The inventory data are obtained from the academic resources and actual experimentation. The data are normalized into similar units and processes described from the Ecoinvent database. The transportation cost is excluded in the analysis and the LCA model is based on the energy mix of Taiwan.

#### *2.4.2. Lab-scale and pilot-scale model*

To investigate the potential environmental impacts and energy analysis of torrefied microalgae bio-char production, a comparative assessment of two model system, (i) lab-scale (ii) pilot-scale model are analyzed.

In this study, laboratory-scale open pond cultivation system is used to provide a baseline for the prospective industrial scale due to its lower energy requirement compared to photobioreactors systems. The lab-scale data for the upstream processes is obtained from [9, 10] while the torrefaction data from the actual measurement is used. Meanwhile, the LCA for the pilot-scale model is performed to evaluate the effect of scale-size from the laboratory-scale experiment. In this study, the upstream process of the pilot-scale model is obtained from [11] and the energy requirement of wood torrefaction from [5] is adopted in the study.

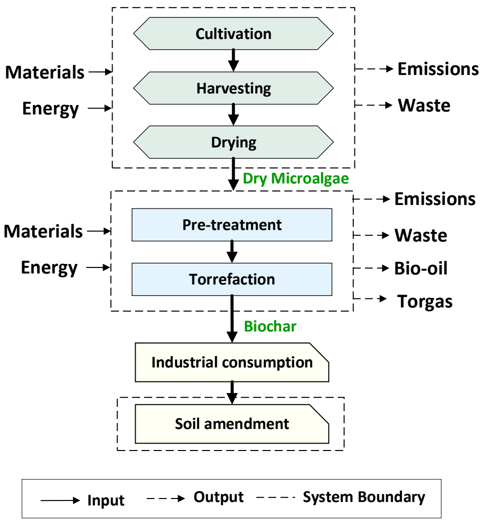


Fig 2 Microalgae bio-char production

## 3. RESULTS AND DISCUSSIONS

### *3.1. Characterized environmental impact*

The environmental impact potentials considered in the study include global warming potential (kg $CO_2$ eq), freshwater eutrophication potential (kg P eq), terrestrial acidification potential (kg $SO_2$ eq), marine eutrophication potential (kg N eq), and particulate matter formation (kg PM10 eq). From the characterization results shown in Fig 3, the torrefaction process has the highest contribution for all environmental impact potential. For the GWP, the torrefaction tallied the highest, contributing to 96% for the laboratory-scale and 76% for the pilot-scale model. Using the inventory analysis, 97% of this is attributed to the nitrogen gas consumption for the laboratory-scale model while 78% for the pilot-scale model.

Based on the analysis, a total of 287.78 and 183.62 kg $CO_2$eq. emissions are obtained for the laboratory- and pilot-scale model when the TSI value is 0.9. The corresponding $CO_2$ emission can be minimized during the cultivation process and when biochar is used as a soil amendment. A total of 1.83 kg $CO_2$ per microalgal biomass is removed from the atmosphere during the cultivation [12]. Meanwhile, the torrefied microalgae biochar, at TSI value of 0.9, has an equivalent of 72.60 % carbon[2]. Therefore, a total of 37 kg $CO_2$ during cultivation can be removed from the atmosphere. Using the stoichiometry, a total of 2.64 kg $CO_2$eq. in soil amendment can be returned to ground for every kilogram of torrefied microalgae biochar.

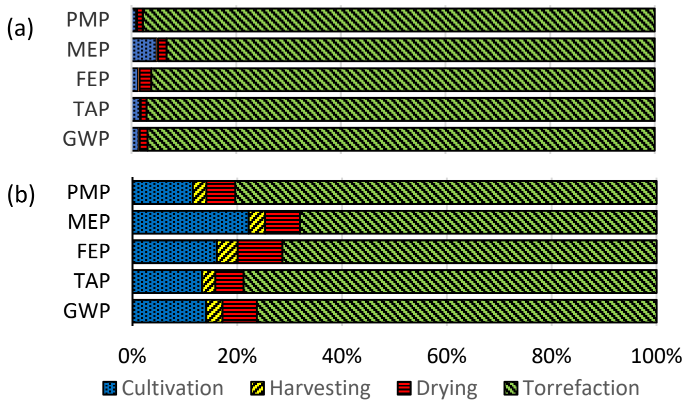


Fig 3 Characterized environmental impact of torrefied microalgae biochar production (a) lab-scale (b) pilot-

### *3.2. Energy Consumption*

The energy comparison for the scenarios was investigated and the results are shown in Fig 4.

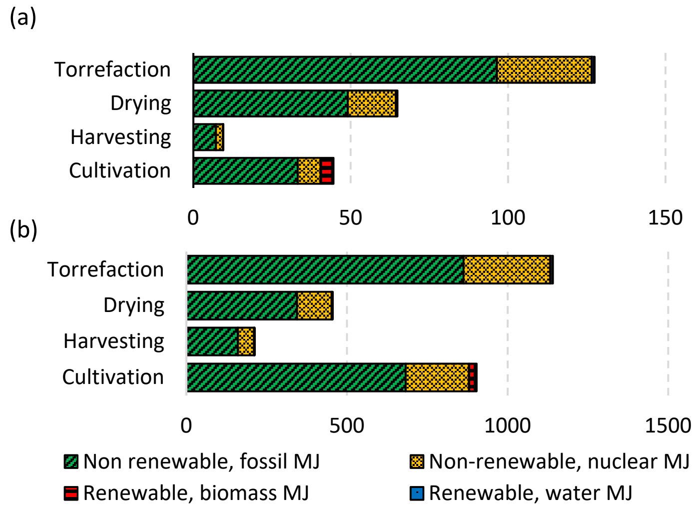


Fig 4 Characterized cumulative energy demand of torrefied microalgae biochar production (a) lab-scale (b) pilot-scale

Similar to the environmental impact potentials, the incorporation of the torrefaction process, for both scenarios, resulted to have the highest contribution. For the total non-renewable fossil, torrefaction corresponds to 51% for lab-scale while 42% for the pilot-scale model.

*3.2. Global warming potential using the torrefaction severity index*

Since torrefaction has the highest contribution for both the environmental impact potential and energy consumption. A corresponding GWP using the TSI is obtained.

In Fig 5, the gradient at the longest duration and highest temperature has the highest corresponding $CO_2$ equivalent. In contrast to the TSI, the residence time has a significant impact to the GWP as compared to temperature. The gradient revealed that with the TSI value of 0.96, 0.51, and 0.13, the torrefaction process corresponding emissions are 0.30 $kgCO_2$ eq, 0.20 $kgCO_2$eq., and 0.05 $kgCO_2$eq. respectively.

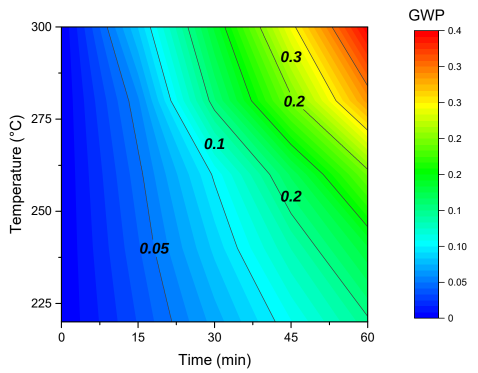


Fig 5 Contour map of global warming potential ($kgCO_2$ eq.)

## 4. CONCLUSIONS

A life cycle assessment has been used in investigating the environmental performance and energy consumption of the torrefied microalgae biochar using torrefaction severity index. A comparative life cycle assessment study from laboratory-scale and pilot-scale of biochar production has been considered. The results show that the torrefaction process has the highest environmental impact and energy consumption due to the nitrogen consumption. The study highlights the torrefaction severity index as a tool for obtaining the corresponding environmental emissions during the microalgae biomass conversion to solid fuel. The resulting contour map, gives insight in the sustainable production of torrefied microalgae biochar. Future work includes the comparative LCA study of non-oxidative and oxidative torrefaction on microalgae biomass to assess the environmental emissions and energy consumption.

## ACKNOWLEDGEMENTS

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