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Review article

Thermal processing of algal biomass for biofuel production

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ABSTRACT

Concerns over the environment and energy security have led to considerable research efforts into the development of renewable alternatives to fossil-based fuels and chemical from biomass. Algae has been identified as the biomass with great potential for utilization in this regard, due to several advantages algae has over terrestrial plants, such as a higher growth rate and photosynthetic efficiency, better CO_2 sequestration, and the ability to grow in non-arable land with low quality water. Conversion technologies, particularly thermochemical conversion, are actively being researched and developed to produce renewable chemicals and fuels. A major advance in this regard is thermal conversion of whole algal biomass, especially wet processing that can significantly reduce the cost of production. This short review looks at major developments in thermal processing of algal biomass with primary focus on the past two years.

1. Introduction

There is increasing global energy demand mostly for transportation fuels, which have been projected to increase by about 56% by 2040 [1]. The majority (>80%) of this demand is currently met by fossil derived fuel reserves (petroleum, natural gas and coal) [1]. The development of renewable and sustainable alternatives to fossil derived fuels and chemicals has become imperative in recent years. This is primarily due to concerns about greenhouse gas emissions and climate change associated with over-reliance on non-renewable fossil fuels, as well as socio-economic and energy security concerns. This has led to the development of several conversion technologies that utilize biomass (lipids, lignocellulosic, carbohydrates, algae etc.) to produce renewable chemicals and fuels.

Algae, especially microalgae, has been recognized as a potential source of biomass for fuels and chemicals utilizing a variety of pathways [2]. Compared to terrestrial plants, algae have a photosynthetic efficiency that is orders of magnitude higher, leading to higher growth rates and biomass yields. Furthermore, algae can be grown on marginal and non-arable land that could not be used for food production, as well as poor quality waters such as seawater, brackish water, along with municipal, agricultural, and industrial waste waters [3]. Several thermochemical conversion technologies are being developed for the production of renewable biofuels from algae including: biodiesel from transesterification, biochar from carbonization, bio-oil or bio-crude from liquefaction/pyrolysis, and bio-syngas from gasification. The present piece focuses on thermal conversion platforms (carbonization, liquefaction, and gasification), with emphasis on breakthroughs over the past two years.

2. Whole algal biomass thermal processing

Microalgae typically grow to a low density that ranges from 1 to 5 g/L [4], although high-density microalgae production of up to 90 g/L has been reported in the literature [5–7], particularly with the use of *Chlorella* sp. The low density of algal cultures is a major drawback in the processing of microalgae as many of the conversion technologies, such as biodiesel production, require dry biomass feedstock. The dewatering/drying step in microalgae processing has been estimated to account for up to 50% of the energy consumption [8] or about 25% of the energy content of the microalgae [9]. As a result, the majority of recent research on the thermal conversion of microalgae has focused on wet processing (hydrothermal processing) of microalgae slurries in conditions ranging from subcritical to supercritical water. The operating temperature has been used to classify the hydrothermal processing of microalgae into carbonization (<200 °C), liquefaction (200–375 °C), and gasification (>375 °C) [4]. The products from the

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different hydrothermal processing vary depending on the conditions with carbonization resulting in the generation of char, liquefaction resulting in the synthesis of bio-oil and gasification producing bio-syngas. Table 1 summarizes some of the recent studies in thermal processing of algal biomass.

2.1. Carbonization

Carbonization, in particular, hydrothermal carbonization is the mildest thermal processing with temperatures in the range of 150–250 °C for varying reaction times. The primary product of carbonization is biochar, which has been proposed to have potential utilization in soil amendment, plant nutrition, and energy generation through combustion or co-firing with coal [10–12]. The prospect of co-firing biochar from microalgae with coal is especially interesting, because it will help make an otherwise non-renewable process partially "green" by incorporating a fraction from renewable resource, thereby reducing the carbon footprint of the process. Carbonization of algae to produce biochar has been reported in the literature in recent years [10,13–20].

Luo *et al.* [17] developed a high-capacity adsorption activated carbon from microalgae biochar, which has potential use in the capture and storage of CO_2 with direct implication for reducing greenhouse gas emissions. In another study, Yu *et al.* [21] used direct carbonization/activation of algal biomass to developed high-capacity supercapacitors and battery anodes. The authors suggested that the developed method/product could have potential application in large-scale production of supercapacitors and lithium ion batteries. Hydrothermal carbonization of microalgae and subsequent fatty acids extraction with solvents was used to demonstrate the possibility of producing fatty acids of high value for nutraceutical application, as well as the conversion of recovered low value fatty acids into fuels through transesterification [15]. Espinosa-Gonzales *et al.* [6] reported the formation of a solid paste (biochar) after hydrothermal processing of high-density high-lipid containing microalgae. The fatty acids were recovered from the biochar through solvent extraction and used in the production of hydrocarbon fuels through pyrolysis.

One of the major drawbacks of carbonization of microalgae is the relatively low value of the primary product, biochar [4]. However, with recent development of high-value applications for biochar, such as use in supercapacitor and lithium ion batteries, there is great potential for the utilization of carbonization processing of algae to produce high value commodities. In addition, if biochar from carbonization of algae is seen as a by-product/co-product obtained during conversion of algal biomass to high-value components, such as high-value fatty acids, the utilization of the by-product/co-product will further improve the profitability of the algal biorefining process. Furthermore, the recycling of the nutrients, particularly in the aqueous fraction after hydrothermal conversions, has been successfully demonstrated by several authors, whereby the aqueous fractions from hydrothermal carbonization were used in the cultivation of microalgae and other microorganism such as oleaginous yeast [14,16,18,22–24]. This further improves the process economics and profitability of algal biomass thermal processing, particularly hydrothermal processing.

2.2. Liquefaction

Thermal liquefaction of algal biomass results in the production of bio-oil: a black, viscous material similar in appearance to crude oil (petroleum). The vast majority of research surrounding thermal processing of algal biomass deals with liquefaction, with particular emphasis on hydrothermal (wet) liquefaction due to its economic advantage over dry algal biomass liquefaction. The quality and composition of bio-oil produced from liquefaction is dependent on the processing conditions, initial feedstock (algal strain), and whether the reaction was conducted as a batch or continuous process [4]. Reaction time and temperature are critical parameters that affect the economic operation of the liquefaction process, with too short reaction times reducing bio-oil yield and too long reaction times resulting in an increase in gas product formation [25,26]. The use of continuous reactor processing helps improve the process energetics through effective energy recycling and reuse, which can significantly reduce production cost [27–29].

There is a wealth of literature on algal biomass liquefaction with several recent reviews [25,30,31]. To improve the energy efficiency of bio-oil production, Pearce *et al.* [32] integrated the hydrothermal liquefaction of algal biomass with concentrated solar power and concluded that the use of concentrated solar power together with nutrient recycling has the potential for economically sustainable bio-oil production. However, they noted that there are concerns of scaled productivity, conversion efficacy, and economic viability that need to be addressed with further experimental application.

Table 1
Summary of algal biomass thermal processing studies.

Process/Feedstock	Temperature (°C)	Time (min)	Biomass concentration (wt %)	Conversion (%)[a]	By product	Ref
Carbonization						
- *Chlorella protothecoides*	280	60	27	60	Aqueous	[6]
- *Chlorococcum* sp.	200	180	N/A	N/A	Aqueous	[17]
- *Nanochloropsis* sp.	180–220	15–30	15	30–47	Aqueous	[15]
- *Enteromorpha*	800	60	N/A	N/A	N/A	[21]
- *Spirulina maxima*	175–215	30	N/A	23–49	aqueous	[10]
Liquefaction						
- *Arthrospira platensis, Tetraselmis* sp.	250–350	30	20	35–40	Aqueous/biochar	[36]
- *Tetraselmis* sp.	310–350	5–30	16	29–68	Aqueous/biochar	[27]
- *Chlorella* sp.	350	1–6	10	37–40	Aqueous/biochar	[34]
- *Saccharin* sp.	350	LHSV = 1.2–1.5	5–22	8–28	Aqueous/gas	[28]
Gasification						
- *L. hyperborean*	400–550	0–120	3–13	N/A	N/A	[45]
- *P. oceanic*	300–600	60	0.04–0.12 g/mL	20–50	Aqueous/biochar	[47]
- *S. almeriensis after lipid extraction*	400–800	N/A	400 mg	70–75	N/A	[38]
- *S. horneri with biomass*	600–750	120	N/A	N/A	Biochar	[40]
- *Scenedesmus obliquus*	650	3	0.71–0.87	N/A	Aqueous	[49]
- *A. obliquus*	600–650	N/A	2.5–5	90–98	Aqueous	[46]

[a] Conversion represents the wt/wt % of primary product (biochar, bio-oil or bio syngas) to initial biomass LHSV = liquid hourly space velocity obtained in the continuous process. N/A = not available.