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Co-liquefaction of swine manure and mixed-culture algal biomass from a wastewater treatment system to produce bio-crude oil

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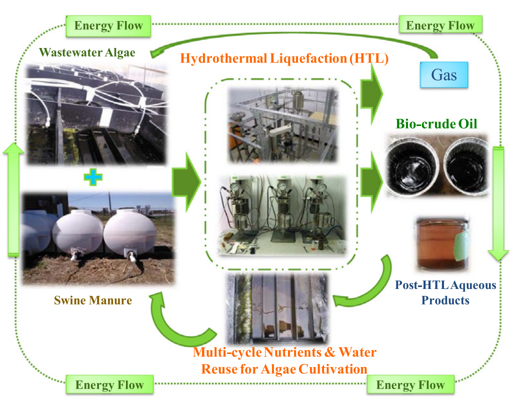
HIGHLIGHTS

- The first work co-liquefied swine manure and algae from wastewater into bio-crude oil.
- Demonstrated comparable energy consumption ratios in contrast to HTL of pure algae.
- The highest bio-crude oil yield was 35.7% based on dry matter.
- Thermal gravimetric analysis showed both light oils and heavy crudes were produced.

GRAPHICAL ABSTRACT



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ABSTRACT

This study explored the feasibility of combining two types of feedstocks, swine manure (SW) and mixed-culture algae (AW) from wastewater treatment systems, for bio-crude oil production via hydrothermal liquefaction. The effect of feedstock combination ratios on the bio-crude oil yields and qualities were investigated. SW to AW ratios (dry weight basis) were 1:3, 1:1 and 3:1 with a total solids content of 25%. Pure SW and AW were also hydrothermally converted at the same reaction condition for comparison. By combining 75% SW with 25% AW, the highest bio-crude oil yield was achieved (35.7% based on dry matter). By mixing 25% SW with 75% AW, the highest heating value (27.5 MJ/kg) was obtained. GC–MS spectra and thermal gravimetric analysis of bio-crude oils revealed that both light oils and heavy crude were produced, averaging 25% and 20% of the bio-crude oil, respectively. Analysis of energy consumption ratios indicated that co-liquefaction of AW and SW is energetically feasible and could be an economically competitive system for bio-crude oil production.

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1. Introduction

Algal feedstock is viewed as a favorable feedstock for next generation bio-energy products. Algae can grow in most water sources (fresh, salty, wastewater, etc.) and on marginal lands, which can reduce competition with food crops for arable lands. To date, algal biofuels research has predominantly focused on culturing algal species with high lipid content for extraction and transesterification to biodiesel. Low lipid content algae, however, typically have higher biomass productivity than high lipid algae and are much more tolerant with stressful conditions such as growing in wastewater [1,2]. This capability also provides an opportunity to combine bio-energy production and waste treatment to mitigate environmental pollution such as eutrophication [1,3]. This new paradigm of integrating bioenergy production with bio-waste treatment using low lipid algae [2,4] is referred to here and elsewhere as Environment-Enhancing Energy (E^2-Energy). This type of system cannot only uptake nutrients from wastewater sources but can also re-release most of the nutrients to support multiple cycles of algae growth and bioenergy production [2,5].

Hydrothermal liquefaction (HTL) converts biomass feedstock into bio-crude oil with high temperatures and pressures. The macromolecules in the feedstock are first depolymerized into light molecules. Subsequently, the unstable fractions are repolymerized into oil compounds [6]. HTL can directly convert feedstock into energy-dense products without drying and thus is more suitable for treating wet feedstocks (e.g. algae) than other thermochemical conversion processes such as gasification or pyrolysis [4,7–9]. In a previous HTL test of *Chlorella* algae, liquefaction produced a self-separating bio-crude oil product when the reaction temperature reached approximately 240 °C. Below 240 °C, green/brown slurries and bio-char were formed instead [4]. Reaction time is another significant factor affecting the formation of bio-crude oil. Swine manure (SW) and algae typically require at least 15 and 10 min, respectively, to form products similar to crude oil or bitumen [10].

Low-lipid algae are a suitable candidate to produce bio-energy via HTL [4,11,12]. While previous studies have concentrated mostly on food grade or pure-culture (axenic) algae, large-scale algal cultivations are difficult to grow consistently as monocultures, particularly for algae cultured in wastewater. Our previous work has demonstrated that mixed-culture algal biomass from wastewater treatment systems (AW) can be an appropriate HTL feedstock for bio-crude oil production [5,13], and several other studies have noted that waste treatment and algal biomass production should be integrated to achieve a net positive energy balance [1,2,14]. With abundant nutrients, such as nitrogen and phosphorus, the liquid fraction of swine manure is an advantageous medium for algae cultivation. Thus, it is expected that swine manure bio-solids and algal biomass could both be available at the same locations, and it would be advantageous to process them both using the same HTL process. Some amount of manure bio-solids will likely be entrained in the algal biomass grown in manure liquids [15,16]. Therefore, this study aims to explore the co-liquefaction of SW and AW for bio-crude oil production in order to help establish an energy-efficient and economically viable approach to treat these biomass mixtures.

Although SW and AW are each individually viewed as promising feedstocks for bio-crude oil production via HTL [2,5,7,17], co-liquefaction of these two mixed feedstock has not been previously reported. This study explored the product distribution, physico-chemical properties, nutrient recovery, and energy balance in the co-liquefaction of SW and AW. To the best of our knowledge, this present study is the first of its kind to systematically evaluate the production of bio-crude oil from combined biomass feedstock of SW and AW. When using wastewater (e.g. liquid portion of swine manure) to culture algae, the contamination by competing microorganisms during the algae cultivation is typically encountered [2,18,19]. The co-liquefaction of swine manure and mixed-culture algal biomass into bioenergy products allows for using two different types of biomass sources and thus can help resolve the contamination of target algal species (e.g. high-lipid algae) during the algae cultivation, and facilitate increased efficiency in converting two renewable resources into sustainable bio-energy products.

2. Experimental procedures

2.1. Feedstock

A mixed-culture algal biomass from wastewater (AW) was directly harvested from a full-scale mixed algal wastewater treatment plant (One Water Inc., Indianapolis, IN) and therefore had a relatively high ash contents (47.5%). Similar ash contents were also found in the algae feedstocks directly harvested from a retention pond and a local wastewater treatment plant (Urbana-Champaign Sanitary District, Champaign, IL) [13,20]. The mixture algal biomass contained microalgae, macroalgae, bacteria and other organisms. The swine manure (SW), which was the same type used in the previous studies [11,20–22], was collected directly from the floor of a grower-finisher barn. Prior to HTL experiment, proper ratios of mixed algal biomass and swine manure were mixed and homogenized using a commercial blender (MX 1000XT, Waring Commercial Inc., Torrington, CT) and then stored in a refrigerator at 4 °C. The total solids of AW and SW were measured as the dry residue at 105 °C, and the corresponding ash contents were measured as the combustion residue at 550 °C. The other macromolecules and chemical compositions such as acid detergent fiber, neutral detergent fiber and lignin were analyzed using the methods of the Association of Official Analytical Chemists (AOAC). Detailed analyses of AW and SW were summarized in Table 1.

Table 1
Characteristics of swine manure (SW) and mixed-culture algal biomass from wastewater (AW).

Feedstock	Proximate analysis (d.w.%)[b]		Ultimate analysis (d.w.%)[b]						
	VM[a]	Ash	C	H	N	O[c]	H/C	O/C	N/C
AW	52.5	47.5	27.9 ± 2.6	3.01 ± 0.5	3.90 ± 0.4	65.2	1.29	1.75	0.12
SW	83.7	16.3	41.1 ± 0.2	5.42 ± 0.09	3.36 ± 0.1	50.1	1.58	0.92	0.07

Chemical composition (d.w.%)[b]					
	Crude fat	Crude protein	Hemicellulose	Cellulose	Lignin
AW	1.70	27.2	3.50	14.4	5.70
SW[d]	20.3 ± 1.5	24.5 ± 1.8	27.3 ± 2.2	3.8 ± 1.4	3.6 ± 1.3

[a] Volatile matter.
[b] Dry weight basis.
[c] O (wt%) = 100 − (C + H + N) (wt%).
[d] Average values were reported based on the previous studies [11,20–22] because the chemical compositions were found to be stable in the same type of swine manure.