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Spatially Explicit Life Cycle Assessment: Opportunities and challenges of wastewater-based algal biofuels in the United States

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A B S T R A C T

This work presented a Spatially-Explicit-High-Resolution Life Cycle Assessment (SEHR-LCA) model for wastewater-based algal biofuel production, by integrating life cycle assessment, GIS analysis, and site-specific Wastewater Treatment Plants (WWTPs) data analysis. Wastewater resources, land availability, and meteorological variation were analyzed for algae cultivation. Three pathways, Microwave Pyrolysis, hydrothermal liquefaction, and lipid extraction were modeled for bio-oil conversion. This model enables the assessment of seasonal and site-specific variations in productivity and environmental impacts of wastewater-based algal bio-oil across the whole U.S. Model results indicate that wastewater-based algal bio-oil can provide an opportunity to increase national biofuel output. The potential production of algal bio-oil can reach to 0.98 billion gallon/yr, nearly 20% of advanced biofuel projection as outlined in the U.S. Energy Independence and Security Act (EISA) of 2007. LCA results shows significant variations among different locations, WWTPs, and operational seasons. Although not competitive to conventional fossil fuel in energy efficiency, wastewater-based algal biofuel could offer significant benefit in controlling GHG emissions. However, spatial analysis shows that only 61% of the total wastewater could be used, based on current land use efficiency for algae cultivation and land availability around each WWTP in a radius where algal biofuel production is energy positive (energy output > energy input). These results indicate that land availability could be a significant challenge for wastewater-based algal biofuels that have not been considered in previous studies. They also suggest that improvement should be made in technological development and system design to increase energy and land use efficiency for full potential of wastewater as a promising resource for algal biofuel production. Although focusing on the U.S. as the case study, the developed methodology could be used for spatially explicit analysis of algal biofuel integrated with wastewater on macro-scale in other regions as well.

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1. Introduction

Algae have unique and desirable characteristics as a source for biofuel, including rapid growth and capability of growing in poor quality water, but there remain a number of challenges before the technology can be deployed at large-scale [1,2]. Key barriers that hinder the utilization of algae biofuels are high cost and limited capacity for scaled-up production of algal biofuel feedstock. Studies indicate that wastewater, currently underused, could be one of the most favorable resources for algae feedstock production, because it (1) provides ample supply of nutrients and water, (2) can support a large capacity for biofuel production (up to 5 billion gallons of algal biofuel per year could be generated with municipal wastewater in the U.S. [3], and (3) can be integrated into existing public infrastructure, rather than creating new industrial systems [4–7].

A number of studies have been conducted to investigate the potential of the synergies of algae biofuels and wastewater, from empirical selection of algal strains to pilot-scale algae cultivation systems and energy conversion pathways [8–11]. Despite such progress and promise, however, there has been no large-scale algae-wastewater facilities emerging yet. To better understand the potential performance of integrated algae-wastewater systems, life cycle assessment (LCA) has been applied to assess these integrated systems. LCA is a widely accepted quantitative accounting tool for evaluating the environmental effects of products, process, or services by computing the energy/material inputs and wastes released to the environment, and also assessing the potential environmental impacts of those energy, materials, and wastes [12]. LCA has become an actively researched area and has been increasingly applied in academic and industrial fields for environmental impact assessments.

Early stage of wastewater-algae LCA studies assessed the environmental performance of wastewater-based algal bioenergy system based on process modeling. Clarens et al. (2010) compared environmental impacts of bioenergy from algae and other territorial crops

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including canola, corn, or switchgrass [13]. They found significant environmental benefits of using wastewater in algae cultivation. Similarly, Davis et al. (2011) and Gallagher et al. (2011) reported that the environmental and economic performance of micro-algal biofuel production are unlikely to be competitive with traditional fossil fuel in the near term, without the replacement of energy-intensive commercial fertilizers [14,15]. In all of these studies, the authors pointed to the need for improved access to low cost, low energy-intensity nutrient (nitrogen and phosphorus) sources, such as wastewater resources, to improve the overall environmental and economic bottom lines. Later on, Mu et al. (2014) evaluated the environmental performance of wastewater-based algal biofuels with a well-to-wheel LCA [16]. Their results indicated that the environmental performance of wastewater-based algal biofuels is generally better than freshwater-based algal biofuels. However, these LCA studies only focused on single site with generalized assumptions, without systematic consideration of geographic diversity, seasonal climate variation, and resource availability. This type of LCA, often referred to as a **Static LCA** using only peak or lumped data, is unsuited to assess national-scale potential and environmental performance of wastewater-based algal biofuel that depend on many factors including quality/quantity of wastewater, climate variations (solar radiation, temperature, and precipitation among others), and land availability.

More recently, a few limited studies applied Geographical Information Analysis (GIS) to analyze the potential production of algal bioenergy with wastewater [17,18]. However, these studies didn't include LCA in their analyses, and, as such, could not answer the question whether wastewater-algae system is truly environmental friendly at large-scale. Furthermore, the data resolution of these GIS analyses was relatively low: using regional data rather than site-to-site specific data. Finally, there were no co-siting analysis of algae facilities and wastewater infrastructure in these studies. This is a critical research gap, because facility siting is one of the most significant challenges faced by wastewater-based algae systems since wastewater treatment facilities tend to be near metropolitan areas with limited land availability, and it is not practical to transport wastewater over long distances [1].

To address these research gaps, the present work develops a High-Resolution-Spatially-Explicit Life Cycle Assessment (HRSE-LCA) model, by integrating LCA, GIS analysis, and site-to-site specific analysis of Wastewater Treatment Plants (WWTPs) and land availability. This model enables the evaluation of seasonal and site-to-site variations in production and environmental impacts of wastewater-based algal biofuels across the whole U.S. This study is conducted with two specific objectives: (1) assess the realistic potential in production of algal biofuels with municipal wastewater resources across the whole U.S., using site-to-site specific GIS-based analyses of resource availability and algae growth model; and (2) evaluate seasonal and geographic variations in environmental impacts of wastewater-based algal biofuels, by integrating GIS-based algae growth model and life cycle assessment. We focus on municipal wastewater because it is the most studied wastewater resources for algal biofuel production, as well as its available data source [6,17–19]. This work extends the literature by integrating geographic diversity, seasonal climate variation, and resource availability into large-scale life cycle assessment of wastewater-based algal biofuels. Although focusing on the U.S. as the case study, the developed methodology could be used for spatially explicit analysis of algal biofuel integrated with wastewater on macro-scale in any other regions as well.

2. Material and methods

The purpose of this study is to evaluate the realistic potential and seasonal/site-to-site variations in production and their implications for environmental performance of wastewater-based algal bio-oil across the whole U.S., based on a HRSE-LCA framework (Fig. 1). The national-scale potential production and environmental performance of wastewater-based biofuels depend on many factors including wastewater resources, climate variations (seasonal and spatial variations), and land availability. To account for these variations, the HRSE-LCA model is composed of four modules, including high-resolution GIS-based spatial resource assessment (Module 1), spatially explicit algae growth model (Module 2), biofuels conversion pathways (Module 3), and LCA (Module 4). Fig. 1 depicts how these four modules are incorporated together and what are the overall processes flows for the modelled system. Specifically, Module 1 (high-resolution GIS-based spatial resource assessment) estimates wastewater resource, nutrient profile, and land availability based on each individual municipal WWTPs across the whole U.S. Module 2 (spatially explicit algae growth model) predicts spatial and seasonal algal biomass production and material/energy input/output by incorporating the results of Module 1 (resource analysis) and spatial/seasonal variations of meteorological data into the algae growth model. Module 3 assesses biofuels production and material/energy input/output for three biomass-to-bio-oil conversion pathways. Based on the results of Module 1–3, Module 4 performs life cycle impact analysis by calculating environmental burdens associated with process operation and upstream input. GIS information (such as temperature, land coverage, and solar radiation among others) were obtained from PRISM, USGS, and NREL, respectively [20–22]. All modules were built in Microsoft Excel, using Crystal Ball Commercial suite for characterization of input and output uncertainty. The following sections briefly discusses the methodology for each Module. Details are provided in the Supporting Information (SI).

2.1. High resolution GIS-based spatial resource assessment (Module 1)

2.1.1. Municipal wastewater

Spatial wastewater resource data for each individual WWTP, including capacity and population served, was extracted from the Clean Watersheds Needs Survey [19] by using "Exist Total Flow" (wastewater generated by population plus infiltration). Data shows that there are around 17,000 WWTPs for the whole U.S., and the yearly flow rate is roughly about 34,200 million gallon/day (1.3×10^8 m^3/day). By filtering out WWTPs with very small capacity (<0.05 MG/D), 12,452 WWTPs with a total capacity of 33,576 MG/D, accounting for 99.7% of total wastewater flow, were included in this analysis. Primary or secondary wastewater effluent were chosen for algae cultivation, as previous studies suggest that solid material contained in wastewater prior to primary clarifier could damage pumps and reduce their operation life [5,23,24]. The nutrient profile (nitrogen, phosphorous, and COD) of wastewater was determined by literature [25,26].

2.1.2. Land availability

National Land Cover Database (NLCD 2011) map, published by USGS, was used for land availability analysis and site selection around each individual WWTP of a total 12,452 WWTPs across the U.S. [21]. Suitable land for algae cultivation is non-agricultural, undeveloped or low-density developed, and non-environmentally sensitive, including grassland/herbaceous, shrub/scrub, and barren land [5,27]. Analysis was performed by considering the land availability in 1, 2.5, 5, 7.5, and 10 km radius distance from each WWTPs. This method has been applied in the study of land availability in Kansas up to 2.5 km ([28]. In this analysis, we extended the radius up to 10 km to analyze land availability for the whole WWTPs around the US. To avoid land overlapping around different WWTPs, Thiessen Polygon method from ArcGIS toolbox was used. This study did not include CO_2 constraint in site selection, as previous LCA studies conclude that CO_2 supply plays a negligible role for wastewater-based algae cultivation [16,18]. However, CO_2 supply could affect site selection, if large amount of CO_2 supply was necessary.

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