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Energy consumption during the manufacture of nutrients for algae cultivation

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ABSTRACT

The effect of nutrient production on life cycle analysis (LCA) of energy use and greenhouse gas emissions for algal biofuels can be significant, yet recent algal biofuel LCAs vary significantly in their estimates for contributions from fertilizer production. Given the uncertainty in emissions associated with fertilizer manufacturing and the possibility that they play a significant role in algae LCA, this report examined nitrogen and phosphorus fertilizer production in the U.S. by way of a detailed examination and analysis of published data. We found that the energy use and emissions of algae fertilizers derive from the manufacturing of just a few key reagents, namely ammonia and phosphoric acid. Under the assumption that large-scale algae growth will utilize commodity chemicals, the life cycle inventory centers on a few processes. We report relatively consistent values in the literature for these processes, suggest representative values to use in future LCA work, and discuss proper handling of fossil carbon in urea.

1. Introduction

Biofuels are being developed as sustainable transportation fuels. Biofuel feedstocks often require fertilizers to achieve economic viability and to improve land-use efficiency. Environmental performance evaluation of biofuels is regularly performed with life cycle analysis (LCA). LCA compares the "whole life" energy consumption and emissions associated with various fuel and transportation options by combining the direct environmental effects of fuel production operations with the environmental effects from associated upstream processes like power production and reagent manufacturing. Fertilizer production is included in biofuel LCA in order to have a system scope (system boundary) comparable to that of petroleum-based fuels (the typical reference scenario).

Nutrient contributions to algal biofuels can be significant: The National Research Council (NRC) [1] identified nutrient demand as a significant sustainability concern for production of algal biofuels from extracted lipids since nutrient recovery from process residuals (non-lipid biomass) and recycling has not been demonstrated at scale. Hydrothermal liquefaction of algal biomass is receiving considerable attention because of its high oil yields, but our analysis of hydrothermal liquefaction data indicated that substantial nitrogen losses may occur via incorporation of nitrogen in the oil product [2].

A recent review by Handler et al. [3] studied several algae life cycle analyses in detail with careful consideration of normalization across the various studies and reported greenhouse gas emissions for various fertilizers employed by those studies. Greenhouse gas (GHG) emissions associated with nitrogen fertilizers ranged from 2.6 kg CO_2e/kg-N to 16 kg CO_2e/kg-N depending upon the type of nitrogen fertilizer employed [3], where mass of CO_2 equivalent (CO_2e) is the global warming potential of all emissions. Thus, it seems that fertilizer production has uncertainty in the associated energy and emissions.

Given the diversity of results for emissions associated with fertilizer manufacturing and the possibility that they play a significant role in algae LCA, we wish to assess whether this diversity is the result of a fundamental diversity of approaches to producing nutrients or whether it arises from uncertainty about the process. Further, while GREET has some of the nutrients discussed below, we wish to document the data provenance and seek to improve the transparency of the analysis methodology to make it available for detailed critique and further improvement. We also wish to extend the nutrient list, where possible.

To these ends, this work presents an analysis of published data regarding nitrogen and phosphorus fertilizer production in the U.S. A market study is considered to identify the most widely used compounds for large-scale operations. From this assessment, the dominant production routes are identified and evaluated. The production processes are analyzed to find the direct inputs of material and energy required to manufacture each fertilizer. The final result is a U.S.-centric life cycle inventory for each of the commonly used fertilizers that can be utilized to update life cycle analyses involving nitrogen and phosphorus fertilizers. The algae growth and processing pathway has many possible configurations and many associated uncertainties.

This study reports largely at the inventory level and intends to support the many possible LCA analyses that can be done. The life cycle

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inventory enumerates energy and material inputs required for each nutrient. Energy inputs describe fuels required directly for the process, e.g., natural gas and electricity. Materials include chemical feedstocks, e.g., natural gas as a source of carbon and hydrogen (rather than as a combustible fuel), and ammonia for the production of urea. The material inputs cascade upon each other and allow total energies to be computed.

2. Methods

The literature describing fertilizer production in detail comprises only a few items, which we summarize here. The Fertilizer Institute (TFI) surveys fertilizer producers in the U.S. and Canada [4]. Their report contains aggregated industry information including energy and raw material inputs for fertilizer production. The European Fertilizer Manufacturers' Association (EFMA) details the Best Available Techniques for producing commodity fertilizers, which includes process designs, energy use, and pollution control for retrofitted and new plant designs [5]. Kongshaug reported the process demands for several fertilizers in Europe [6]. This report was based on knowledge as an employee in the fertilizer industry. A thesis by Davis and Haglund gives a more detailed examination on European fertilizer production including prevailing trends and transportation [7]. Portions of Davis and Haglund's work were based on the report and personal communications from Kongshaug. Hydrocarbon Processing (HP), an industry publication company, writes “Petrochemical Processes” that details many process designs and their respective energy uses for petrochemical processes, which includes ammonia and urea production [8]. Other publications also detail fertilizer production energy, but these works tend to restate the information in these few sources. For example, the Department of Energy's “Energy and Environmental Profile of the U.S. Chemical Industry” [9] sources the energy production data for the ammonia and urea processes from the HP 1999 report [8] and nitric acid process data come from the EFMA 1999 study [10]. For that reason, our analysis tends to rely on these primary sources so that it does not bias towards duplicates of the same data.

2.1. Nitrogen fertilizers

Nitrogen is a necessary nutrient for many cultivated crops. A total of 10.4 million metric tons of nitrogen (MMTN) were used as fertilizers in the U.S. in 2009 [11]. A variety of nitrogen fertilizers are used in the U.S., either as solid products, liquid solutions, or direct application of ammonia. Table 1 shows the usage rates for each of the nitrogen-containing fertilizers as well as the percentage of the nitrogen fertilizer share in the U.S. that it represents. Nitrogen solutions in this context are mixtures of urea and ammonium nitrate.

Each commodity nitrogen fertilizer production process begins with ammonia as a feedstock. Urea is formed by reaction of ammonia and carbon dioxide; ammonium phosphates are formed by reaction of ammonia and phosphoric acid; ammonium nitrate is a product of ammonia and nitric acid, where nitric acid also is made from ammonia. Nitrogen fertilizers can also be obtained through mining and as coproducts of processes, but these routes are not considered here as they are an insignificant portion of the market.

As ammonia is the starting basis for all of these fertilizers, it is the focus of this analysis. U.S. ammonia production and consumption will be assessed, followed by detailing the production processes and resource needs for manufacture. The other nitrogen fertilizers will then be assessed, reviewing production methods and inputs. Economic Research Service [12] data includes an additional “other” category which is not shown in Table 1. This category consists of combination ammonia-based fertilizers such as mixtures of calcium ammonium nitrate, ammonium nitrate, and ammonium sulfate. The path to produce them is similar, in that they originate with ammonia feedstocks. As this “other” category is not characterized in terms of the average nitrogen content, it is not shown in Table 1. The “other” category accounts for less than 13% of the fertilizer market by weight nitrogen. Thus, the fertilizers listed in Table 1 capture the majority of the nitrogen fertilizer market. The usage share of each fertilizer listed in Table 1 is relative to only the fertilizers shown in Table 1.

2.1.1. U.S. ammonia market

Roughly 80% of manufactured ammonia goes to nitrogen fertilizers [13]. The nitrogen content of the fertilizer is used as a basis for fertilizer statistics, e.g. 1 kg of ammonia contains 0.82 kg of nitrogen, so that 1.22 million metric tons of ammonia is 1 MMTN. The U.S. has an estimated annual capacity of 9.19 MMTN in ammonia, with a production of 8.17 MMTN [13]. Another 5.62 MMTN are net imported annually, for a total of 13.79 MMTN import and production in the U.S. Combined, Canada and Trinidad and Tobago export 5.20 MMTN to the U.S. [13].

Ammonia manufacture currently uses hydrocarbons as a chemical feedstock and as a process heat source. Over 90% of U.S. production is fueled by natural gas based processes, although Honeywell uses renewable methane from landfill gas to offset 15% of the natural gas consumption in the Hopewell plant [14]. The rest of the ammonia production capacity is met by petroleum coke or coal gasification systems, each with 0.3 MMTN of capacity [15,16].

The majority of the U.S. ammonia imports come from Trinidad and Tobago, which utilize natural gas based plants [17]. Canada exports 0.94 MMTN as ammonia to the U.S. [13]. Novachem's ethylene plant in Joffre, Alberta produces hydrogen from ethane dehydration which feeds Agrium's ammonia process in Joffre [18]. This accounts for 0.38 MMTN of the Canadian capacity. The rest of the 4.42 MMTN capacity Canadian market is natural gas fueled [19]. Combining these two source countries with the U.S. market, 12.77 of the 13.37 MMTN, or 95%, of the U.S. ammonia consumption are from natural gas processes.

The proportion of the U.S. ammonia market that comes from natural gas is summarized in Table 2. The remaining 0.4 MMTN of ammonia imported by the U.S. from Russia and Ukraine are not included in these statistics as little information is available about the feedstocks, and this represents a minority of the ammonia supply. Although ammonia can be manufactured from a variety of feedstocks, natural gas is almost the entire basis of U.S. supplies. For that reason, we will focus on processes that utilize natural gas as both feedstock and process fuel.

2.1.2. Ammonia production process

Ammonia production is based on the Haber process wherein nitrogen and hydrogen react in the gas phase to form ammonia. Details of this process are taken from the European Fertilizer Manufacturers' Association and are shown in Fig. 1 [5]. Natural gas based processes involve

Table 1
Nitrogen fertilizers and their use in the U.S. [12].

	Ammonia		Ammonium				Nitrogen solutions		
Type	Anhydrous	Aq.	Nitrate	Sulfate	Di-phosphate	Mono-phosphate	Poly-phosphate		Urea
Formula	$\mathrm{NH_3}$	$\mathrm{NH_3}$	$\mathrm{NH_4NO_3}$	$\mathrm{NH_4SO_4}$	$\mathrm{(NH_4)_2HPO_4}$	$\mathrm{NH_4H_2PO_4}$			$\mathrm{(NH_2)_2CO}$
Use (MMTN)	3.01	0.08	0.22	0.25	0.38	0.26	0.26	3.12	2.30
Use (%)	30%	1%	2%	2%	4%	3%	3%	32%	23%