Decarbonizing Agriculture through the Conversion of Animal Manure to Dietary Protein and Ammonia Fertilizer

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Abstract

The decarbonization of agriculture faces many challenges and has received a level of attention insufficient to abate the worst effects of climate change and ensure a sustainable bioeconomy. Agricultural emissions are caused both by fossil-intensive fertilizer use and land-use change, which in turn are driven in part by increasing demand for dietary protein. To address this challenge, we present a synergistic system in which organic waste-derived biogas (a mixture of methane and carbon dioxide) is converted to dietary protein and ammonia fertilizer. This system produces low-carbon fertilizer inputs alongside high-quality protein, addressing the primary drivers of agricultural emissions. If the proposed system were implemented across the United States utilizing readily available organic waste from municipal wastewater, landfills, animal manure, and commercial operations, we estimate 30% of dietary protein intake and 127% of ammonia usage could be displaced while reducing land use, water consumption, and greenhouse gas emissions.

Keywords

sustainability; microalgae; biogas; fertilizer; food supply

1. Introduction

The agricultural subsector of the industrial economy will be difficult to decarbonize due in part to its heavy reliance on energy-intensive nitrogenous fertilizers, such as ammonia, and its inefficient methods of producing dietary protein in the form of livestock. Agriculture as a whole represents ~9% of total emissions in the US, with livestock management contributing ~4% (U.S. Environmental Protection Agency, 2016). Nearly 50% of the energy consumed by an average US farm is embodied in nitrogenous fertilizers, resulting in substantial carbon dioxide emissions since over 90% of the ammonia produced in the US is derived from natural gas; the methane in natural gas is reformed to generate hydrogen and carbon dioxide, with the hydrogen being used for ammonia production and the carbon dioxide being emitted to the atmosphere (Richardson and Kumar, 2017; U.S. Geological Survey, 2017). Decarbonizing the production of ammonia is challenging due to the necessity of energy-dense chemical feedstocks (e.g. natural gas), and therefore carbon-free electricity (solar and wind power) by itself does not provide an impactful solution. Over 80% of total agricultural production in the US is for animal feed, resulting in significant land use and greenhouse gas emissions (Graham-Rowe, 2011); privately owned pasture and rangeland account for 27% of all land area in the contiguous US, with the majority of such used for cattle grazing (U.S. Natural Resources Conservation Service, 2018). A growing global population and shifting social demographics are increasing the demand for food rich in high quality protein, and the US is expected to play a significant role in meeting future demand (Tiwari et al., 2017). The global demand for animal-based protein is expected to double by 2050 (Tiwari et al., 2017). As the demand for dietary protein grows, the US agricultural system will strain due to lack of arable land and freshwater, and the environment will be impacted through a continued rise in greenhouse gas emissions. Therefore, the agricultural subsector of the industrial US economy is ripe for innovative solutions that conserve land and water and reduce greenhouse gas emissions without limiting dietary protein production.

Microalgae have the potential to serve as a sustainable source of high quality protein for human health. *Chlorella* and *Spirulina* are established nutritional supplements due to their proven health benefits (Caporgno and Mathys, 2018; Kent et al., 2015; Wells et al., 2017). Microalgae strains commonly used for biofuel research, including *Nannochloropsis*, *Scenedesmus*, and *Dunaliella*, have recently shown great potential as nutritional supplements (Kent et al., 2015). Animal feed is another promising application for microalgae supported by a multitude of successful trials in which corn and soy diets were partially substituted with whole and defatted algal biomass for cattle, pigs, chicken, and salmon (Drewery et al., 2014; Ekmay et al., 2014; Gatrell et al., 2014; Gong et al., 2019; Kiron et al., 2016; Madeira et al., 2017). However, large scale deployment of microalgae-substituted animal feed is currently challenged due to the high costs of algal biomass production, remaining uncertainty in feed effectiveness, and the strict nutrient profiles required by commercial animal feed producers. Therefore, incorporating microalgae in the human diet might be more feasible in the near-term since direct consumption of microalgae by humans is potentially more cost-effective, metabolically efficient, and environmentally beneficial than indirect consumption via animal feed. The essential amino acid indices (EAAI) of the aforementioned algal strains are close to 1.0, meaning the protein compositions include amino acids essential for optimal human health. In addition to high quality protein, microalgae provide nutritious omega 3 & 6 fatty acids, vitamins, and essential minerals; some strains exhibit anti-cancer, anti-inflammatory, and anti-oxidant properties (Kent et al., 2015). The environmental benefits of substituting animal and plant-based proteins with microalgae are substantial, including reduced land use, water consumption, and greenhouse gas emissions; compared with soy, microalgae produce approximately 15 times more protein per unit area (Bleakley and Hayes, 2017). Therefore, a shift towards meeting dietary protein demand with microalgae has great potential to benefit society and the environment. Unfortunately, the costs associated with constructing and operating freshwater microalgae farms are significant, as detailed by the US National Renewable Energy Laboratory's (NREL) recent techno-economic analysis (Davis et al., 2016). Additionally, the bioavailability of microalgal proteins must be enhanced though energy-intensive processing prior to human consumption (Bleakley and Hayes, 2017). However, technological advancements, government support, and a renewed interest in optimizing microalgae farms for food and feed production, instead of biofuels, are lowering costs and pushing microalgae farms closer to reality (Davis et al., 2016). According to NREL's techno-economic model, nutrients comprise 78% of the variable operating costs of an open pond microalgae farm; the costliest nutrients are carbon dioxide, ammonia, and diammonium phosphate (DAP) (Davis et al., 2016). Currently, the vast majority of carbon dioxide and ammonia produced in the US is derived from fossilized carbon resources. Ideally, microalgae farms of the future will use nutrients sourced from renewable sources of carbon, such as biogas from anaerobic digestion.

NREL has analyzed the feasibility of producing biogas from major organic waste streams in the US, namely those associated with wastewater, landfills, animal manure, and commercial waste (National Renewable Energy Laboratory, 2013); commercial waste includes industrial, institutional, and commercial organic waste. NREL considers these organic waste resources as "low-hanging fruit" due to their underutilization and low cost (National Renewable Energy Laboratory, 2013). The biogas potential for the US is much greater if lignocellulosic biomass resources are included with organic waste resources. The majority of research and development into biogas technologies has focused on using the methane component (~60% of biogas) as a substitute to natural gas for power production. Converting the renewable chemical energy locked within biogas to electricity may not be best the method of utilization given the aforementioned difficulties with decarbonizing the agricultural subsector of the industrial economy. Instead, dedicating biogas to the production of chemical energy-dense agricultural products, such as ammonia and dietary protein, is an interesting approach that has received little attention. Herein, we use data from NREL's detailed analyses on biogas and microalgae production to design a synergistic system for the conversion of organic waste-derived biogas to algal protein and ammonia fertilizer, as shown in Figure 1 (Davis et al., 2016; National Renewable Energy Laboratory, 2013).

2. Materials & Methods

The synergistic system is designed and modeled using process data, assumptions, and conversion efficiencies as detailed in the Figure 2 and the Supplementary Information. The system is modeled to account for all mass flows, without any inclusion of energy flows since this information is not pertinent to the study. Biogas is assumed to be generated at each source of organic waste and then cleaned, dehydrated, pressurized, and transported via pipeline to a centralized facility for separation of methane and carbon dioxide, ammonia synthesis, and microalgae cultivation. The sources of organic waste include those associated with wastewater, landfills, animal manure, and commercial waste (National Renewable Energy Laboratory, 2013); commercial waste includes industrial, institutional, and commercial organic waste. The quantities of biogas available from each source of organic waste are taken from NREL's review, which includes a geospatial plot of biomethane availability (National Renewable Energy Laboratory, 2013). Small scale steam methane reforming is used to synthesize ammonia and provide a stream of CO_2 for microalgae cultivation. The design of the microalgae farm is based on the freshwater open pond biorefinery developed by NREL, in which high purity nutrients are used to cultivate microalgae (*Scenedesmus* sp.) (Davis et al., 2016); the composition (wt%) of the microalgae are 13.2% protein, 30.1% lipids, 52.8% carbohydrates, 2.4% ash, and 1.6% cell mass. The techno-economic model for microalgae production developed by NREL is used to quantify mass flows for a 1000 acre operation (Davis et al., 2016). Dietary Reference Intakes established by the National Institute of Health are used to estimate the total daily protein intake by all men, women, and children in the US (Berryman et al., 2018); the average daily protein intakes (g protein/ kg body weight) are 0.87 for ages 1-3, 0.76 for ages 4-13, 0.72 for ages 14-18, and 0.66 for ages above 19. See the Supplementary Information for total protein consumption by men and women of all ages in the US.

3. Results and Discussion

If all available organic wastes are fully utilized, this system has the potential to supply 127% of the entire US demand for ammonia and 30% of the demand for dietary protein while reducing net greenhouse gas emissions and opening up vast areas of pasture and rangeland for other purposes. NREL's geospatial plot showing the potential biomethane production from various organic wastes across the US is used to estimate the potential production capacity of algal protein in each US county, as shown in the Supplementary Information (National Renewable Energy Laboratory, 2013). Interestingly, the areas with the largest potential for biogas generation are also suitable for microalgae growth (Oak Ridge National Laboratory, 2016).

Many researchers have investigated the use of anaerobic digestates as nutrient sources to microalgae growth, but this approach is technically difficult to implement for food production due to the variation in digestate composition and concerns over fecal pathogens, among other factors (Moreno-garcia et al., 2019; Stiles et al., 2018; Zhu et al., 2019); NREL's work indicates first generation microalgae farms will require high purity nutrients for reliable, continuous operation (Davis et al., 2016). Only one strain of microalgae was considered in the analysis (*Scenedesmus* sp.) with a protein content of 13.2%, and therefore the potential for dietary protein substitution could be greater if other strains of microalgae are used – other strains have >40% protein. Notably, less than 2% of the ammonia produced by the system is used for microalgae growth, thereby generating excess ammonia in an amount equal to 127% of US ammonia demand. In addition, 32.2 Mt-CO_2 are utilized for microalgae production per year if implemented across the US. See Table 2 for a summary of the input and output mass flows and land area required for conversion of all organic wastes in the US to ammonia and algal protein using the synergistic system.

Among the various sources of organic waste, we believe animal manure has the greatest potential for near-term impact using the proposed system. We envision farming areas where feed crops are grown for livestock and organic waste is anaerobically digested to serve as biogas inputs to a centralized microalgae farm (1000 acres), as shown in Figure 2. Methane reforming and ammonia synthesis technologies have historically operated at large scale using the Haber-Bosch process, however, recent advancements are enabling the use of modular systems to synthesize ammonia with high efficiency (thyssenkrupp, 2019). Therefore, the centralized microalgae farms cost-effectively produce ammonia on a relatively small scale (122 t-NH_3/day). A total of 93 centralized microalgae farms of 1000 acres each are required to utilize all the available biogas from animal manure in the US, and 384 farms of the same size to fully utilize biogas from all organic waste streams. Notably, the microalgae farm land area required for complete conversion of organic waste-derived biogas to algal protein would demand less than 1% of pasture and rangeland used today in the US (U.S. Natural Resources Conservation Service, 2018). The algal protein would be sold for human consumption and the excess ammonia fertilizer would be purchased by local farming communities.

Further comprehensive investigation into the economic viability of such a system is required, however, published studies indicate the economics of microalgal food products are more favorable than microalgal fuel products (Caporgno and Mathys, 2018; Kent et al., 2015; Wells et al., 2017). In addition, the localized production of ammonia fertilizer should reduce costs for nearby farming operations. Regarding policy support, microalgae production has seen impressive policy gains in recent years, the largest milestone being the recent 2018 Farm Bill, which designated algae a high-priority for research and extension initiatives, as well as amending the Biomass Crop Assistance Program to allow for algae (Conaway, 2018). For this vision to become realty, social acceptance of algae-based food products must continue to advance through innovative culinary practices and public studies demonstrating health benefits. Developing and optimizing systems such as the one presented herein will help maintain the United States' status as a world leader in agricultural production as the stresses of climate change, global population, and a shifting socio-economic spectrum stress the fossil carbon-, land-, and water-demanding agricultural system society is reliant upon.

4. Conclusions

The level of attention aimed at decarbonizing agriculture has been insufficient to ensure a sustainable future. The global demand for dietary protein is increasing rapidly, thereby requiring the development of innovative agricultural practices. Agricultural products are highly dependent on ammonia-based fertilizers derived from fossilized carbon precursors dense in chemical energy, such as natural gas. Therefore, renewable, energy-dense sources of carbon, such as biomethane, deserve serious consideration as sustainable alternatives for the production of agricultural products. The proposed system provides an impactful option to fully utilize biogenic sources of carbon for the production of agricultural products, namely ammonia and algal protein.

E-supplementary data of this work can be found in the online version of the paper.

Conflicts of Interest: Authors declare no conflicts of interest.

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Figures

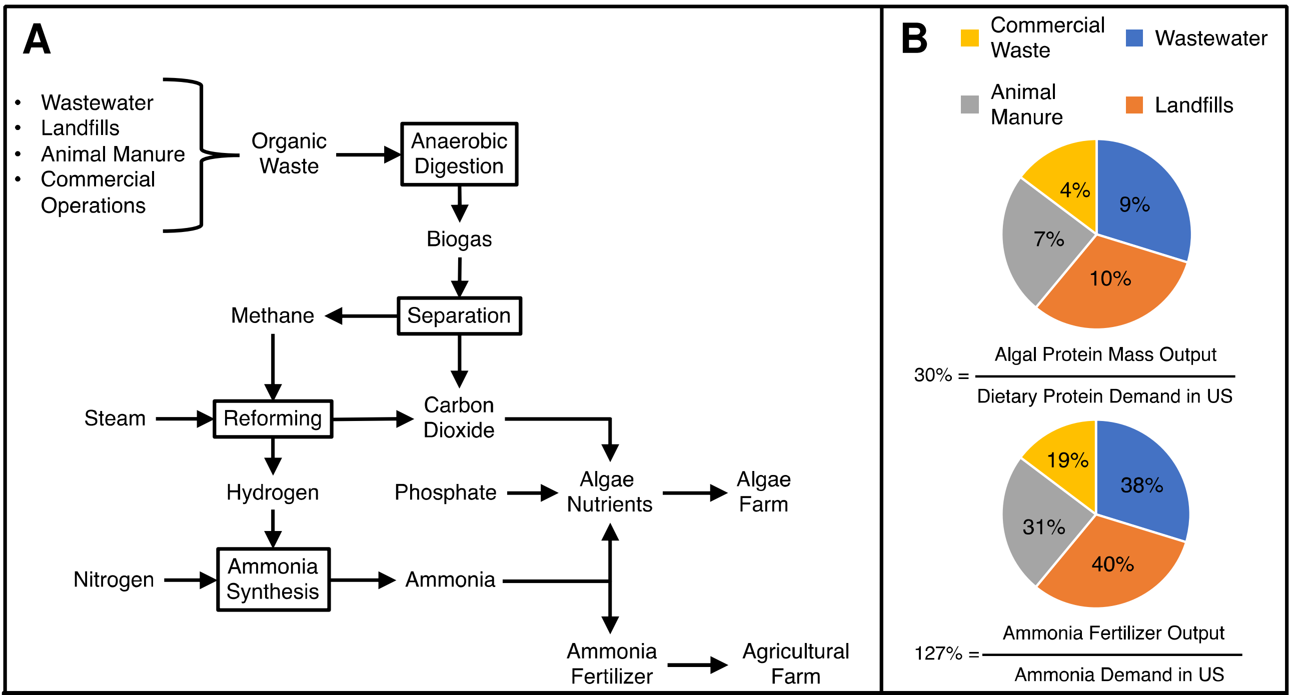

Figure 1. A) A synergistic system in which organic waste is converted to algal protein and ammonia fertilizer (Davis et al., 2016; National Renewable Energy Laboratory, 2013). B) The potential for displacement of dietary protein and ammonia fertilizer if full utilization of organic waste sources across the US is realized. Commercial waste includes industrial, institutional, and commercial organic waste (Berryman et al., 2018; U.S. Geological Survey, 2017).

Table 1. Technical parameters used in modeling the synergistic system

Density of biogas (kg/m^3)	1.15
Density of CH_4 (kg/m^3)	0.67
Density of CO_2 (kg/m^3)	1.84
Biogas vol% CH_4	60%
Biogas vol% CO_2	40%
Biogas separation CO_2 yield	95%
Biogas separation CH_4 yield	95%
Reforming H_2 yield	90%
Reforming CO_2 yield	90%
NH_3 synthesis yield	90%

Table 2. Summary of the input and output mass flows and land area required for conversion of all organic wastes in the US to ammonia and algal protein using the synergistic system.

	Synergistic System Inputs & Outputs (Mt/year)				
	Wastewater	Landfills	Animal Manure	Commercial Waste	Total
Biogas	6.71	7.04	5.47	3.32	22.55
Biogas: CH_4	2.22	2.33	1.81	1.10	7.46
Biogas: CO_2	4.09	4.29	3.33	2.02	13.72
Reformed H_2	1.00	1.05	0.81	0.49	3.36
Reformed CO_2	5.50	5.77	4.48	2.72	18.47
CO_2 to Algae Farm	9.59	10.06	7.81	4.74	32.20
Total NH_3	5.10	5.35	4.15	2.52	17.13
NH_3 to Ag. Farm	5.00	5.25	4.07	2.48	16.80
NH_3 to Algae Farm	0.10	0.10	0.08	0.05	0.33
Algal Protein	0.51	0.54	0.42	0.25	1.72
Algal Lipids	1.17	1.23	0.95	0.58	3.93
	Land Area (acres)				
	Wastewater	Landfills	Animal Manure	Commercial Waste	Total
Land Area of Algae Farms	114185	119829	92997	56517	383527
% of US Pasture & Rangeland	0.022%	0.023%	0.018%	0.011%	0.073%

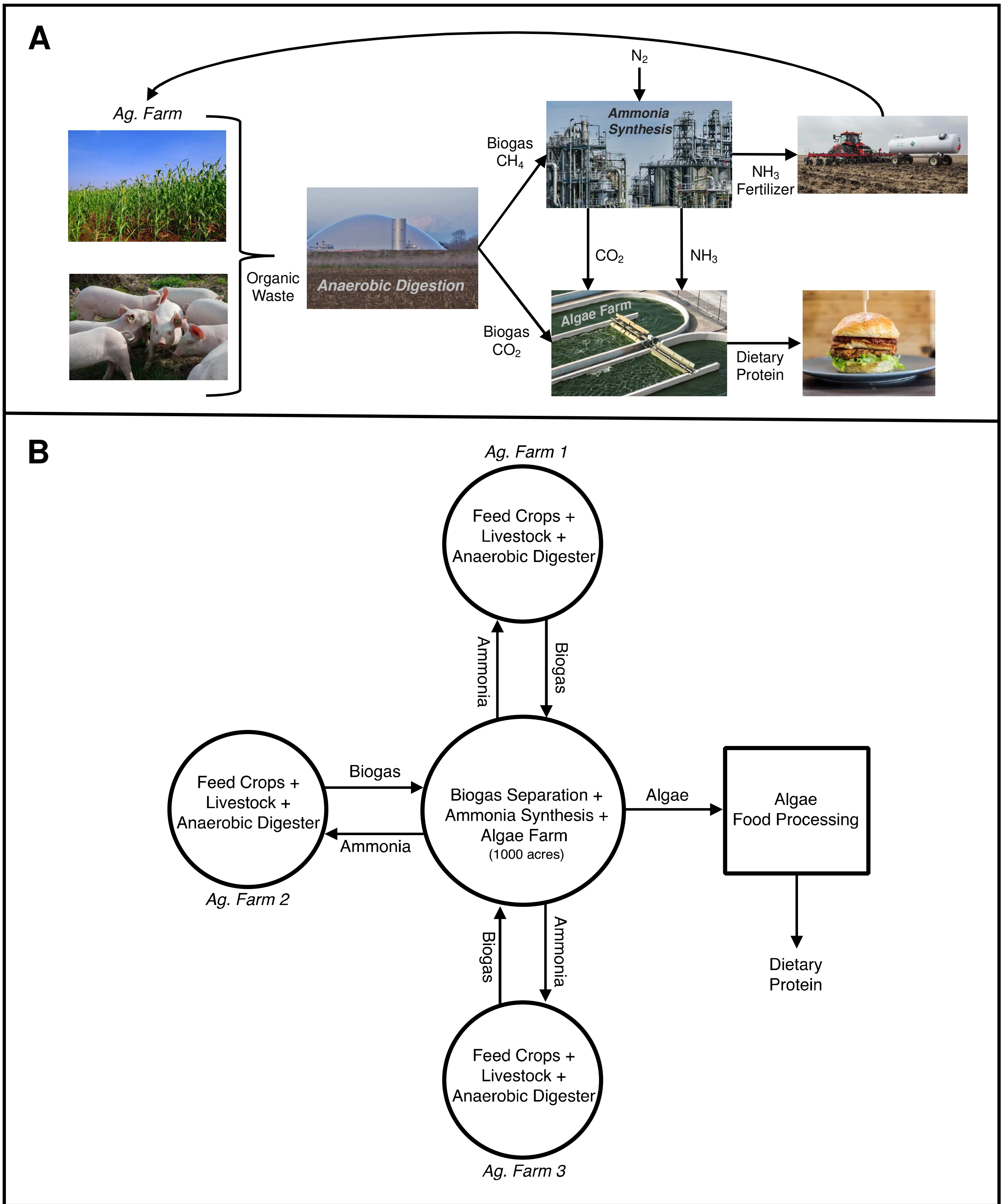

Figure 2. A) A simplified diagram showing the flow of mass from an agricultural farm to final products; see Figure 1 for a more detailed mass flow diagram. B) An example of a synergistic system with 3 agricultural farms and 1 centralized algae farm. A total of 93 centralized algae farms of 1000 acres each are required to utilize all the available biogas from animal manure in the US, and 384 farms of the same size to fully utilize biogas from all waste streams.

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Graphical Abstract