POTENTIAL EFFECTS OF THE INTEGRATION OF MICROALGAE WITH WASTEWATER: WATER FOOTPRINT AND RESOURCE REQUIREMENTS

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ABSTRACT

High solar energy conversion efficiency of microalgae has led to its evaluation as a feedstock for biofuels and bioproducts. Nutrient and water consumption of microalgae is a proposed resource barrier for large-scale production. This study assesses the nutrient requirements and water footprint (WF) of a microalgae biofuel production system. The nutrient resource modeling includes assessment associated with multiple process technologies for a 60 billion gallon fuel production level. Nutrient flow and mass balance was assessed for three production process scenarios. Total nutrient requirements are reported and compared to availability from three different supply sources. The water assessment includes modeling four different fuel conversion pathways in 5 geographic locations, characterized by high biomass and oil yields, with results for water withdraw, consumption, and lifecycle WF reported. Net lifecycle WF with co-product credits varies with geography and conversion pathway between 21 and 47 m_3 GJ^{-1}. The work focuses on sensitivity to microalgae nutrient requirements, and wastewater as a nutrient source.

1. INTRODUCTION

Ever-growing demand for fuel worldwide has generated instability in the supply chain. The increase in fuel demand –and thus fuel prices – has increased the volatility of economies worldwide. One option for decreasing market variability is to find alternative forms of fuel, whose added supply and competition will naturally drive prices down. Additionally, fossil fuels are a limited resource that will eventually be depleted, which creates a long-term need for alternative fuel sources. These immediate and long-term fuel needs have sparked much interest and research in finding alternatives to fossil fuel.

One promising option for renewable fuel is growing microalgae and harvesting its oil, which can be refined to serve as a drop in diesel fuel replacement. Microalgae are especially appealing because of their ability to be grown on non-arable land, to use water sources other than freshwater, and to absorb atmospheric CO_2 as well as CO_2 from combustion sources.

Research has provided much scientific insight about the possibilities as well as the foreseeable obstacles to be overcome for commercial-scale biofuel production via microalgae. When considering resource requirements, much of the focus of the research to date has been into sunlight availability, associated productivity rates, land consumption, and water consumption. The nutrient and water requirement for algae growth and processing is a topic often neglected or minimalized in available literature. Two key nutrients microalgae require are nitrogen and phosphorus. Terrestrial crops require these nutrients also, as fertilizer, so microalgae and food crops could potentially compete. This makes understanding the required nutrient inputs a key component for accurate scalability assessments, which need to be addressed.

Wastewater and seawater are frequently discussed as potential growth mediums for microalgae, which already contain a mixture of water and nutrients. Yang et al. (1) claim that using sea/wastewater eliminates the need of all nutrients except phosphate. Rosch et al. (2) cite that the use of wastewater could reduce nutrient addition for nitrogen and phosphorus by approximately 55%. However, justification is not offered for these claims. Numerous questions remain for understanding the scalability of microalgae cultivation for fuel production. This study helps fill the knowledge gap on key questions, including what the nutrient requirements and water consumption will be to meet DOE 2030 renewable fuel goals, and whether those needs can be met using available resources.

2. METHODS

Two independent assessments have been performed, nutrient requirements and WF. The methods are thus divided into two sections, 1) the nutrient resource modeling and 2) water footprint modeling methods.

2.1 Nutrient Resource System Model

A diagram of the fuel production process studied for the nutrient assessment is shown in Fig. 1. Mass balance calculations were performed to determine the required system inputs for a desired level of fuel production. The baseline model included basic process steps of growth, harvest (dewatering), lipid extraction, transesterification, and recycling via anaerobic digestion (AD). The model included losses to the environment at each process step, as well as accounting for a filter on the post-harvest water and on the post extraction water. These filters would remove any biomass that slipped through the process and the filters would be emptied into the AD. The inputs to the modeling effort include defining microalgae characteristics, fuel production level, and process variables. The baseline scenario assumes the lipid-extracted algae (LEA) and biomass from the harvest and extraction filters went to the AD for nutrient recovery. These system calculations were performed for three production scenarios. The following sections outline, by scenario, the values selected for each of the system parameters and the justification for each choice. A summary of the values is then provided in TABLE 1.

2.1.1 Baseline Scenario

Microalgae Characteristics for Production: Published values for lipid content cover a wide range, and 30% was selected as a mid-range, realistic value to expect from an actual large-scale growth system. (3, 4,5) The hydrogen content of the microalgae was selected to be 7.5%. This is the average value reported by Zelibor et al. (6) A biomass carbon content of 50% was selected, and is the generally accepted value. (7) The percent of lipids that are phospholipids was 25%, which is the average value reported by Chen et al. (8) A C:N:P ratio based on the Redfield ratio was assumed, 106:16:1.

Production Process: A fuel production level of 60 billion gallons per year (BGY) was selected, corresponding to the DOE 2030 goal. A standard process loss of 1% was selected based on a large-scale production system. This applies to a loss in transesterification, extraction, harvest, and growth. The percent of oil left behind in extraction was 5%, and the percent of biomass passing unaffected through the extraction process was 10%.(4) The harvest/dewatering process can have multiple setups, and Frank et al. (4)

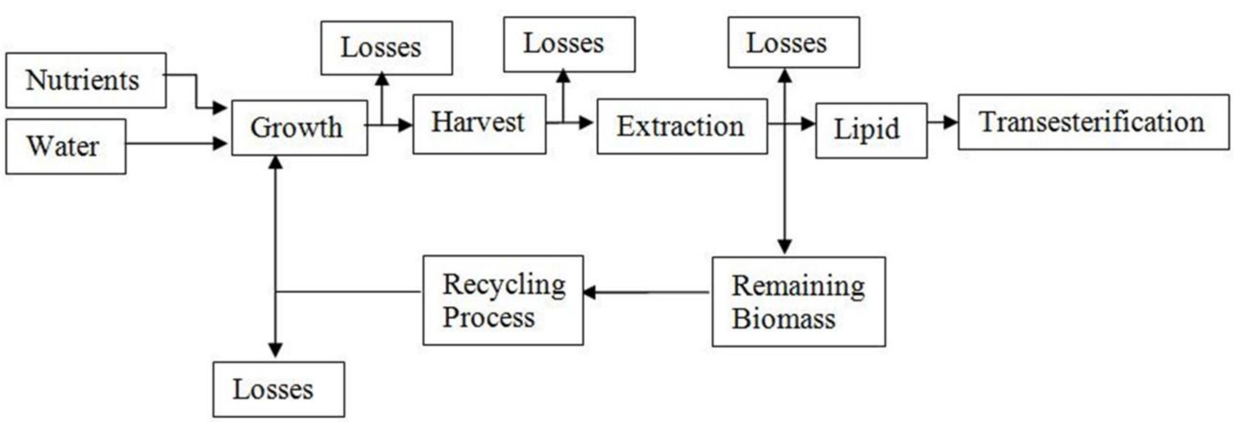

Fig. 1: Diagram of the system model studied.

provide several sources for the determination of their process parameters. The same dewatering process parameters were employed in this study, which are dissolved air flotation with a 10% biomass loss and centrifugation with a 5% biomass loss. For the purposes of this study, the two loss values were combined for an overall 14.5% biomass loss in dewatering. This biomass is assumed to be caught by a filter and sent to the AD. In growth, 99% nitrogen uptake by the microalgae was used. (9) A carbon dioxide absorption rate of 85% was selected for the baseline. (4,10)

Recycling Process: Frank et al. (4) provide several sources for their determination of nitrogen recovery through AD. They determine that 80% nitrogen recovery with 5% volatilization is probable, which, when combined, provides 76% nitrogen recovery. For phosphorus recovery, 70% was used. (11) The performance of the AD system was modeled based on the experimental results of Quinn et al. (12), 31.5/33.4 gVS/g TS for whole biomass, and 88.5/98.6 g-VS/g-TS for LEA. The average value for the methane yield from biomass was assumed to be 0.43 L-CH_4 g-VS^{-1} and 67% methane (12, 13). Methane yield and composition for LEA was assumed to be 0.22 L-CH_4 g-VS^{-1} and 59% methane (12, 14) It was assumed that all biogas would be burned and reused in the growth phase. A 10% CO_2 loss was assumed in this process.

2.2.2 Optimistic and Conservative Scenarios

Surveying available literature regarding process yields and microalgae characteristics provides a range of possible values for system parameters rather than a distinct expectation. The purpose of the optimistic and conservative scenarios was to account for that range. The range represents the best and the worst values that can be expected.

Microalgae Characteristics: The C:N:P ratio was given 166:20:1 for the optimistic case, as presented by Smith (15). This increases the C:N ratio by approximately 20% from the baseline. For the conservative case, 79:16:1 was selected to provide a decrease of the C:N ratio by the same percentage. Lipid content was selected to be 40% for the optimistic case and 20% for the conservative case. This provides ±10% from the baseline and represents values near the extreme ends of what can be expected from a large-scale production system. (3, 4,5) The hydrogen content was selected as 6% for the optimistic case and 9% for the conservative case. (6) The 50% carbon content used in the baseline was kept constant for each optimistic and conservative scenarios. The percentage phospholipid content was taken as 5% for the optimistic scenario and 30% for the conservative. For the optimistic value, results and assumptions from various articles were considered. Chen et al. (8) report values ranging from 18% - 37% phospholipid content. Other sources, including Frank et al. (4) have concluded that phospholipid content will be small enough to be negligible. The conservative value is based on the high value reported by Chen et al. (8)

Production Process: The 60 BGY fuel production level was kept constant across all scenarios so they could all be compared. The baseline standard process loss was cut in half for the optimistic case and doubled for the conservative case, corresponding to 0.5% and 2%, respectively. The percent of lipid left behind in extraction and the percent of biomass passing unaffected through the extraction process were both varied by ±50% of their baseline values corresponding to 2% and 8% for the optimistic and conservative scenarios respectively. Losses for the biomass passing through extraction were changed to 5% and 15% for the two cases. For biomass loss in harvest/dewatering, the optimistic scenario considered only a centrifuge with a minimal biomass loss of 2%. The conservative scenario assumed a 20% loss, increased based on alternative harvesting technologies, from the baseline value of 14.5%. The baseline value for nitrogen consumption by microalgae of 99% is actually below the value reported by Fagerstone et al. (9), 99.6%, so for the optimistic scenario 100% was used. The conservative scenario assumes a 1% decrease of the baseline assumption. In the Aquatic Species Program Report, Sheehan et al. (16) report 90% CO_2 absorption into the growth medium. This value was used for the optimistic scenario. The conservative case was calculated based on the operation of an outdoor PBR system corresponding to an absorption of 2% for the CO_2. (25)

Recycling Process: Nutrient recovery through AD was selected to be 85% for the optimistic case and 60% for the conservative case for both nitrogen and phosphorus. (11, 4) Methane production for whole biomass was selected as 0.80 L-CH_4 g-VS^{-1} at 62% methane content for the optimistic scenario and as 0.25 L-CH_4 g-VS^{-1} at 72% methane content for the conservative scenario. These were the high and low values reported by Quinn et al.(12) and Sialve et al. (13) Methane production for LEA was selected as 0.31 (L CH_4/g VS) at 49% methane and 51% CO_2 content for the optimistic case and 0.14 (L CH_4/g VS) at 69% methane and 31% CO_2 content for the conservative scenario. These were the high and low values reported by Quinn et al. (12) and Ehimen et al. (14) The total CO_2 process loss was halved for the optimistic case and doubled for the conservative case, being 5% and 20% respectively. The 20% loss in the conservative case was accounted for in the calculations with only 98% of the biogas making it to the burning process, and an 18% process loss in combustion and recovery.

2.2 Water Footprint System Model

Water consumption is defined as the total water that is not returned to a water body. (17) Water footprint (WF) is the freshwater consumption of a process or product per functional unit. The functional energy unit for the model is a unit of biofuel based on its lower heating value (LHV). (18) The WF is therefore quantified as cubic meters of water per unit of energy of biofuel produced (m^3GJ^{-1}). The temporal unit is 1 calendar year, with the number of cultivation days varying for each cultivation facility due to geographically specific climatic conditions. The cultivation season is approximated using a thermodynamic model of a photobioreactor cultivation system.(19) Model assumptions include the growth facility is active after the first full thaw of the cultivation system, and is dormant after ice first forms on the surface of the growth system.

TABLE 1: SUMMARY OF SELECTED PARAMETER VALUES FOR EACH SCENARIO IN NUTRIENT ASSESSMENT

Parameter Name	Baseline Scenario	Optimistic Scenario	Conservative Scenario
Biofuel prod.	60 BGY	60 BGY	60 BGY
C:N:P	106:16:1	166:20:1	79:16:1
Lipid content	30%	40%	20%
Hydrogen %	7.50%	6%	9%
Carbon %	50%	50%	50%
Phospholipid %	25%	5%	30%
Standard Loss	1%	0.5%	2%
Lipid extraction %	15%	4%	26%
Nitrogen loss	1%	0%	2%
CO_2 absorption	85%	90%	2%
Nitrogen recovery	76%	85%	60%
Phosphorous recov.	70%	85%	60%
Algae CH_4 yield	.43*	.80*	.25*
LEA CH_4 yield	.22*	.31*	.14*
CH_4 Burn %	100%	100%	98%
Algae CH_4 %	67%	62%	72%
LEA CH_4 %	59%	49%	69%
CO_2 Loss	10%	5%	18%

*units are liters of methane per gram volatile solids (L-CH_4 g-VS^{-1})

Three different metrics of WF are analyzed in this study: blue, green, and lifecycle. (20,21) The blue WF is a metric of the direct water withdrawal of a process. The green WF is a metric representing the difference between the water lost through feedstock evapotranspiration, soil moisture evaporation, and the water gained through precipitation. The lifecycle WF metric is the most comprehensive; accounting for the direct water consumption in the process, the upstream water consumed in materials and energy production, and the water credits that are returned by the co-products generated in the biofuel production process.

A systems model of water inputs to the microalgae-to-biofuels process is used to assess the WF in these metrics for the microalgae-based biofuels process. The system boundary for this study is the fuel cycle up to the delivery to the consumer. The stages studied within this boundary include cultivation, harvesting, dewatering, oil extraction, fuel conversion, and fuel transportation and distribution. (22) For the modeled process, green WF only accounts for precipitation, as basin evaporation is directly accounted for through makeup water, and disturbances to soil quality or moisture content are assumed negligible. The lifecycle boundary includes upstream water use, which is defined as the water consumed to produce materials and energy inputs to the microalgae-to-biofuel process, such as electricity, fertilizers and photobioreactor material.

For the blue and green WF calculations, this study uses a process approach, where the water consumption is modeled or measured at each stage of the microalgae-to-biofuels process. For the lifecycle WF calculations, this study uses a hybrid method combining process and economic input-output approaches.

Analysis of WF requires the modeling of both evaporation and precipitation. The open basin collects water from precipitation during the cultivation period, and avoids additional water withdrawal to supply evaporated water. Mean monthly precipitation data is estimated from a 20-year average database. (23) Evaporation is a significant component of the water consumption because the water basin is an open pool where water evaporation can occur. As recommended in Farnsworth (24), water evaporation rate is assumed to be 75% of the measured pan evaporation rate, with mean monthly pan evaporation rate modeled as the average of a 15 year database of Class A pan evaporation data. (24)

To characterize the WF of microalgae biofuels for this baseline scenario, five locations were chosen, in states with the highest algae biofuels production, TABLE 4.

The WF analyses were performed based on a photobioreactor-based microalgae-to-biofuels production plant. The photobioreactors are vertically oriented polyethylene panels with thermal and structural support provided by a water basin. (25) The photobioreactor cultivation facility has a footprint of 315 hectares that includes growing and processing facilities. (22) De-watering is performed by using a centrifuge with centrate recycling. The microalgae oil is extracted through wet extraction process that uses ethanol/hexane solvent. (22)

The data for the four conversion processes considered in this study are based on four models of soybean oil-to-biofuels conversion, due to similarities in lipid profiles of microalgae and soybeans: (i) biodiesel (BD), (ii) green diesel type 1 (GD1), (iii) green diesel type 2 (GD2) and (iv) renewable gasoline (RG). BD is the biofuel obtained with simple transesterification of crude oil. GD1 is the biofuel obtained through hydrocracking, hydrotreating and hydrogenation of lipids using the SuperCetane process. (26) GD2 is the

TABLE 2: TOTAL SYSTEM INPUT REQUIREMENTS FOR EACH SCENARIO

	Baseline	Optimistic	Conservative
Biomass to be grown (Mmt)	1002	587	1850
N Input to system (Mmt)	23.1	6.7	96
P Input to system (Mmt)	5.2	1.1	14.4
CO_2 Input to system (Mmt)	1540	738	161000
H_20 Consumption (BGY)	179	84	395

biofuel obtained through dehydroxygenation and decarboxylation of lipids, using the Ecorefining process. (27) RG is gasoline obtained from catalytic cracking of lipids. Refining data are drawn from the ANL GREET 1.8d model and its associated process inventories. (18) Microalgae biomass and lipid production is modeled as a function of time, temperature, photosynthetically active radiation, nutrient levels, culture density, and 16 species-specific biological variables. (28)

3. Results and Discussion

Results and discussion are divided into two sections, nutrient assessment and water footprint analysis.

3.1 Nutrient Input Requirements

The system mass balance calculations were performed for three different scenarios – baseline, optimistic, and conservative. The amount of biomass, nitrogen (N), phosphorus (P), and carbon dioxide (CO_2) that are required as system inputs for the three scenarios are presented in TABLE 2. These inputs are defined as the total new nutrient requirements. Finally, hydrogen content in the grown biomass was used to determine water (H_20) consumption. Note that this result is only referring to water consumption through the fixation of hydrogen in the biomass. The results of this study show that in order produce 60 billion gallons of fuel, it is expected that approximately 1 billion metric tons (1000 Mmt) of biomass will need to be grown. This number is nearly cut in half for the optimistic case and nearly doubles for the conservative case. This wide range is due to uncertainty in the system parameters.

Despite nutrient recycling, more than one-third of the nitrogen and phosphorus is lost in the production process. The largest contributor to the nutrient losses from the system is the inefficiency of AD. Approximately one-fourth of the nutrients are lost during this recovery process. Nutrient losses from the system also came from the standard loss to the environment that is inherent in every process, and from phosphorus lost to phospholipids.

3.2 Nutrient Availability

Growth nutrients for the cultivation of microalgae are expected to be in the form of fertilizer or by utilizing a growth medium that already contains nutrients, such as municipal wastewater or seawater. The wastewater treatment facilities in the US process 32 billion gallons of wastewater per day. Wastewater nutrients are frequently assumed to be readily available at minimal cost and meet large-scale microalgae cultivation demand. The baseline model was used to determine the nutrient requirements and corresponding availability from various sources, TABLE 3.

TABLE 3: COMPARISON OF BASELINE NUTRIENT INPUT REQUIREMENTS TO AVAILABLE NUTRIENT SOURCES

Resource:		Nitrogen	Phosphorus
Seawater	Input Needed	19 TGY	28 TGY
	As % of Colorado River Annual Flow	620%	940%
Wastewater	Input Needed	186 TGY	173 TGY
	% of total Available in U.S.	1600%	1500%
Fertilizer	Input Needed	23.1 Mmt	5.2 Mmt
	% of U.S. Consumption	98%	125%
Wastewater & Fertilizer	% of U.S. Fertilizer Consumption after use of 100% of U.S. Wastewater	92%	117%

Results show current nutrient sources such as seawater or wastewater will not be able to supply the required nutrients at DOE 2030 alternative fuel scale. Wastewater is only capable of providing approximately 6% of the required nutrients, and so remains as a possible supplement but not the ultimate nutrient source and growth medium. Seawater

TABLE 4. LOCATION AND CORRESPONDING PRODUCTION CHARACTERISTICS FOR THE FIVE US LOCATIONS EVALUATED

STATE	LOCATION NAME	LOCATION		GROWING	BIOMASS YIELD	OIL YIELD
		Latitude	Longitude	days	$kg\cdot ha^{-1}\cdot year^{-1}$	$m^3\cdot ha^{-1}\cdot year^{-1}$
ARIZONA	TEMPE	33.5°N	-111.9°W	365	52,947	23.70
CALIFORNIA	HAYFIELD PUMP PLANT	33.6°N	-114.7°W	365	52,616	23.51
COLORADO	JOHN MARTIN	37.9°N	-100.7°W	274	36,400	16.29
MONTANA	YELLLOWTAIL	45.5°N	-100.4°W	236	29,481	12.97
NEBRASKA	NORTH PLATTE	40.7°N	-99.0°W	254	33,736	15.11

contains nutrients and could be utilized, but the amount necessary would not be energetically favorable.

3.3 Water Footprint Results

The microalgae biofuel WF is sensitive to the temporal and areal productivity of biofuel, based on the WF defined as water consumption per unit of biofuel energy. Across the five locations modeled in this study, yearly averaged microalgae oil yields range from 13 to 23.7 m^3 $ha^{-1}yr^{-1}$. As shown in TABLE 4, the Arizona and California locations present the longest cultivation seasons, corresponding to the highest oil productivities.

For microalgae-based biofuels, the blue WF varies as a function of fuel conversion pathway and location between 21 and 79 m^3 GJ^{-1}, as shown in TABLE 5. Averaged among the locations and conversion pathways, the process water use for feedstock cultivation, harvesting, and extraction accounts for 97.7% of the blue WF, and the fuel conversion accounts for 2.3% of the blue WF, with details presented in TABLE 5. The green WF is negative, representing a water gain in the water basin due to precipitation. The green WFs for biodiesel and GD2 are the lowest among the four fuel conversion pathways, with GD1 and RG bring the highest.

3.4 Lifecycle Water Footprint

Whereas the blue and green WFs provide metrics of local water use or withdrawal, the lifecycle WF provides a system-level metric of net water consumption for the process of producing microalgae-based biofuels. The lifecycle WF includes the inventories of the process water consumed, the upstream water consumption associated with energetic and material inputs for each stage of the fuel cycle, and does not include the water credits associated with the coproducts.

Without considering coproduct credits, the microalgae lifecycle WFs vary among geographies and fuel conversion pathways between 151 and 473 $m^3\cdot GJ^{-1}$. This variation is primarily due to the effects of the fuel conversion pathways. The BD pathway is the least water-consumptive, with lifecycle WF varying between 21 and 79 $m^3\cdot GJ^{-1}$. The RG pathway has the highest water-consumptive pathway with lifecycle WF varying from between 41 and 79 $m^3\cdot GJ^{-1}$. GD1

TABLE 5: BLUE, GREEN AND LIFECYLCE WF FOR THE 5 US SITES EVALUATED. LIFECYLCE WF DOES NOT INCLUDE CO-PRODUCT CREDITS. ALL VALUES ARE PRESENTED IN $m^3\cdot GJ^{-1}$, AVERAGED ACROSS ALL 4 CONVERSION PATHWAYS. NEGATIVE VALUES APPEAR IN PARENTHESIS.

	Blue WF		Green WF	Lifecylce WF
STATE	**Process water**	**Fuel conversion**		
ARIZONA	23 – 44	0 – 1.5	(2) – (5)	26-46
CALIFORNIA	39 – 76	0 – 1.5	(1) – (2)	44-79
COLORADO	32 – 62	0 – 1.5	(5) – (12)	30-53
MONTANA	30 – 59	0 – 1.5	(8) – (17)	24-44
NEBRASKA	27 – 51	0 – 1.5	(8) – (17)	21-41

and GD2 have intermediate conversion efficiencies and water consumptions.

4. Conclusion

The two modeling efforts focused on the nutrient and water resource requirements for large-scale microalgae to biofuel processes. Modeling results show nutrient sources such as wastewater and seawater alone cannot provide the required resource to achieve 60 BGY of biofuel production. Further scalability assessment shows the entire U.S. market for fertilizer would be required in order to achieve the nutrient requirements at this production level.

Sensitivity analysis shows improvements in the process can reduce nutrient requirements and improve large-scale feasibility. The greatest impact will come from increased nutrient recovery in the recycling process. This could come through improvements in anaerobic digestion or through alternative recycling processes such as hydrothermal liquefaction. The next greatest impact can potentially come from microalgae composition. Lipid content and C:N:P ratio have a high effect on the nutrient requirements. Finally, any reduction in other system process losses and phospholipid content will impact the nutrient requirements.

To quantify the water resource impacts of microalgae-based biofuels, this study has calculated the WF using a variety of biofuel pathways and WF metrics. The productivity of microalgae and its corresponding WF is shown to vary across geographical regions of the US. From the lifecycle WF perspective, the water intensity of microalgae-based biofuels is highly dependent on the processes technologies. Although microalgae biofuels scenarios can be constructed with low WF, the results of this study show that under a variety of metrics, both local water consumption and lifecycle water consumption will be a significant resource constraint for large-scale microalgae biofuels production.

Microalgae are a promising source for fuel production to meet DOE 2030 goals. The nutrient and water requirements for this level of fuel production are currently beyond the capacity of the U.S. to provide, but system improvements can potentially make the goal attainable.

5. Disclaimer

6. References

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