Nutrient Resource Requirements for Large-scale Microalgae Biofuel Production: Multi-pathway Evaluation

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Abstract

Growing demand for energy worldwide has increased interest in the production of renewable fuels, with microalgae representing a promising third generation feedstock. This study presents the use of a modular engineering process model, informed through literature, to evaluate the nitrogen and phosphorus resource demand of five microalgae to biofuels production systems. The baseline scenario, representative of an economically viable large-scale production system, includes sub-process models for growth, dewater, lipid extraction, anaerobic digestion, and biofuel conversion. Baseline modeling results combined with current US resource availability from fertilizer and wastewater show nitrogen and phosphorus requirements represent a potential barrier to the large-scale development of microalgae based biofuels. Baseline results show municipal wastewater sources can provide sufficient nutrients to produce 3.8 billion gallons of fuel per year, corresponding to 6% of the DOE goal of 60 billion gallons per year. Results from modeling of alternative production scenarios shows hydrothermal liquefaction to be a promising technology in terms of resource consumption and the use of lipid extracted algae as a value-added co-product is limited due to nutrient recovery requirements for scalability. Optimistic and conservative process scenarios are simulated to bound the total resource demand and represent practical best and worst case scenarios.

Keywords: biofuel; microalgae; model; nutrients; scalability

Abbreviations: AD-anaerobic digestion, BGY-billion gallons per year, CO₂-carbon dioxide, C:N:P-carbon:nitrogen:phosphorus, DOE-Department of Energy, HTL-hydrothermal liquefaction, LCA-life cycle assessment, LEA-lipid-extracted algae, Mmt-million metric tons, TEA-techno-economic analysis, TGY-trillion gallons per year, TS-total solids, VS-volatile solids

1. Introduction

Increasing volatility in energy availability and cost, as well as the environmental impacts of fossil fuel use, has resulted in the domestic production of renewable fuels. The US Department of Energy (DOE) has quantified the level of interest in, and need for, renewable fuel through the establishment of a goal for the year 2030 that 30% of US transportation fuel or 60 billion gallons per year (BGY) will be derived from renewable sources [1]. A variety of second and third generation terrestrial based feedstock options exist, but microalgae have several advantages, including higher solar energy conversion efficiency, the ability to be grown on non-arable land, utilize impaired waters, and integration with various low value nutrient (nitrogen and phosphorus) sources including wastewater and point source carbon dioxide (CO₂) [2, 3]. Furthermore, microalgae are of interest in wastewater treatment for the removal of nitrogen and phosphorus [4-6]. The many advantages make microalgae one of the more promising feedstocks for production of renewable biofuels.

Researchers have evaluated the requirements, implications, and barriers to microalgae biofuel production at the scale required for the DOE 2030 goal through techno-economic analysis (TEA), life cycle assessment (LCA), and resource assessment. The majority of the TEAs and LCAs to date have developed system models of large-scale production facilities in an effort to quantify the energy and mass requirements, with results limited to financial costs and environmental impact [7-24]. Results from TEAs have suggested that higher value co-products from the lipid extracted algae (LEA) could improve

the economics of biofuel production. The impacts of selling a co-product on the nutrient requirements of the system have not been fully characterized [14, 18]. Published LCAs contain results focused on energy use and carbon emissions, with minimal analysis regarding scale-up limitations based on nutrient requirements [15, 23, 24]. Resource assessments have evaluated in detail the impact and availability of land, water, and CO₂ requirements on the scalability of microalgae based biofuels, with results showing land does not currently represent a resource limitation, while water and CO₂ will be limiting resources in some regions of the US [25-32]. Pate et al. [33] performed a high-level, low-granularity evaluation of the water, land, CO₂ and nutrient requirements for large-scale production based on a mass balance assessment. Model details include only microalgae cultivation and omit all other steps of the biofuel production system. Their results provide the order of magnitude to expect for resource demand, but are inadequate due to the limited model scope. Venter et al. [32] perform an assessment which includes land, water, CO₂ and nutrient requirements of various pathways that is constructed on a system model comprised of sub-process models. However, the sub-process models for harvest, extraction (lipid extraction or HTL), and conversion to fuel is limited to individual efficiency factors. Additional nutrient assessments make claims that seawater and wastewater can potentially provide the nutrients necessary for large-scale microalgae production, but provide no justification for these claims [34, 35]. The feasibility of integrating wastewater with microalgae cultivation as a source of water and nutrients for microalgae growth, as well as effective wastewater treatment has been established [2, 3, 36-38], but such studies have not extended results to evaluate the potential scalability at levels consistent with DOE renewable fuel goals. Despite the knowledge gained through previous TEAs, LCAs, and resource assessments, a need remains for thorough evaluation of the nutrient demand for large-scale biofuel production from microalgae.

Large-scale engineering system models are needed to quantify the nutrient requirements in the microalgae to biofuel process and evaluate the potential for various nutrient sources such as fertilizer

and wastewater to meet the corresponding resource needs. This study assesses the large-scale resource requirements of multiple pathways of the microalgae to biofuel production processes. The work utilizes a modular engineering process model of the microalgae to biofuel production system to evaluate the nutrient requirements for baseline, optimistic, conservative, LEA co-product, and hydrothermal liquefaction (HTL) conversion process scenarios. The engineering system model, representative of a near-term large-scale system, includes growth, dewater, lipid extraction, anaerobic digestion (AD), and biofuel conversion processes for a system boundary that is consistent with the “well to pump” of LCA modeling. Optimistic and conservative scenarios were developed to encompass the variability of process efficiencies within the baseline system, account for advancements in processing technology, and provide bounds for the resource requirements. Alternative production processes were modeled which include a system based on the production of fuel with LEA co-products and the utilization of an alternative conversion and nutrient recycling process, HTL. Total nutrient requirements were determined for an annual fuel production level of 10 billion gallons. Discussion focuses on the results for resource requirements for the five production scenarios, system scalability within the US, a comparison of results to previous resource assessments, and sensitivity of resource results to model inputs to inform future research areas for decreasing nutrient requirements.

2. Methods

1 A modular engineering system model, designed to track mass flow, was developed in order to
2 quantify the resource requirements of a large-scale microalgae to biofuel production system while
3 incorporating the ability to evaluate alternative process technologies. Modeling work was performed at
4 a plant production level of 10 million gallons of gasoline equivalent per year [39, 40]. The process
5 model, shown in Figure 1, includes 24 inputs used to characterize the production system with process
6 losses and efficiencies in each step included. Five production scenarios were modeled, with the

following sections outlining the input values and justification for each system parameter. A summary of the fundamental system parameters and assumptions for each of the five microalgae to biofuel production scenarios used in this study is summarized in Table 1 with additional details presented in the supplementary material.

Figure 1. Engineering process model of the microalgae to biofuel production system used to model five production scenarios. Detailed system models for each scenario presented in supplementary material

2.1 Baseline, Optimistic, and Conservative Scenarios

The baseline scenario is intended to represent a near-term, large-scale microalgae to biofuel production system [7, 8, 10, 11, 15, 22, 23, 41-48]. The baseline scenario is based on mature technologies and for example includes a lipid extraction system as this technology has been demonstrated at commercial scale for other oil based feedstocks [49-51]. The model includes growth, dewater, lipid extraction, biofuel conversion, and resource recycling through AD as the process steps [14, 15, 22, 52]. In order to establish bounds on resource demand, optimistic and conservative scenarios are modeled. The optimistic scenario is comprised of the most efficient values reported in literature for each process, typically at bench or lab-scale, and represents the biofuel production system with the lowest nutrient demand. The optimistic scenario requires advancements in each of the processing technologies to be viable at large-scale. The conservative scenario represents technologies that have been demonstrated on a commercial scale, and results in the highest nutrient demand [8, 53, 54]. It is

recognized that at commercial scale, processes will inherently have a loss to the environment or a waste stream, so a loss is included in each process and standardized due to uncertainty. The baseline process model loss was assumed to be 1% and was cut in half for the optimistic case and doubled for the conservative case, corresponding to 0.5% and 2%, respectively, with justification presented in each sub-process.

2.1.1 Growth

The production system modeled is assumed to produce microalgae that is rich in lipid from nitrogen induced stress at a rate of 13 grams ash free dry weight per square meter per day ($\text{g m}^{-2} \text{d}^{-1}$) [52, 55]. A lipid percentage of 30% was selected for the baseline as a mid-range, realistic value to expect from a large-scale growth system, with 40% and 20% representing the optimistic and conservative cases, respectively [14, 15, 27, 33, 52, 54]. The percent of lipids that are phospholipids was assumed to be 25% for the baseline, the average value reported by Chen et al. [56], and was taken as 5% for the optimistic scenario and 30% for the conservative scenario [15, 56]. The processing of biomass in a timely manner will impact the composition of the microalgae with the biorefinery assumed to be co-located with cultivation. The modeled system included a minimal process loss based on minimal delay in processing [57-59]. A biomass carbon content of 50% was assumed for the baseline and unchanged for the optimistic and conservative scenarios as it is a generally accepted value [15, 33, 60, 61]. The hydrogen content of the microalgae was selected to be 7.5%, 6%, and 9% for the baseline, optimistic, and conservative values, respectively [62]. The elemental composition of the microalgae is modeled through a molar carbon : nitrogen : phosphorus (C:N:P) ratio, which can vary depending on the state of growth [55, 63]. The C:N:P ratio assumed for the baseline system is 106:16:1 based on the operation of a large-scale photobioreactor production facility cultivating *Nannochloropsis* [64, 65]. The C:N:P ratio was assumed to be 166:20:1 for the optimistic case, as presented by Smith [66], which increases the C:N ratio by approximately 20% from the baseline. For the conservative case, 79:16:1 was selected to

provide an equal but opposite deviation from the baseline as the optimistic scenario. The range for the microalgae composition is intended to capture the variability expected in various species and requirements of alternative growth platforms.

Growth was modeled based on a batch cultivation system. Nitrogen absorption in the growth phase is assumed to be 99% over the course of the batch, with the remainder being absorbed by competitive species or converted to di-nitrogen mono-oxide [67, 68]. Nitrogen uptake in the optimistic and conservative scenarios was assumed to be 99.7% and 98%, respectively [67, 69].

2.1.2 Dewatering

Multiple possible dewatering processes exist for the baseline scenario. The selection of the baseline technologies was driven by performance and large-scale viability. This study assumed integration of dissolved air flotation [15, 70-72] with a 10% biomass loss followed by centrifugation [15, 71, 73] with a 5% biomass loss, which were combined for an overall 14.5% biomass loss going from 1% solids to 20% solids [15]. The lost biomass was assumed to be caught by a filter in the water recycling process and sent to the AD. Filtration of the recycled water is required to ensure minimal contamination in the growth system. The optimistic scenario considered only a centrifuge with a minimal biomass loss of 2%, and the conservative scenario assumed a 20% loss that would be expected from low-energy harvesting technologies such as bio-flocculation [39].

2.1.3 Lipid Extraction and Conversion

The lipid extraction process contains two fundamental avenues for lipid loss, first in lipids that are unavailable to extraction and second in the incomplete recovery of the extracted lipid. For the baseline, it is assumed 10% of the biomass passes through the system without lipid extraction. An additional 5% of the available oil is assumed to be non-recoverable [15, 74]. The unaffected biomass was assumed to be sent to the AD. Both of the extraction parameters were varied by $\pm 50\%$ of their baseline

values for the optimistic and conservative scenarios, which corresponds to 5% and 15% for the biomass passing through, and 2% and 8% for available but un-extracted oil [15]. For the conversion of extracted lipid to biofuel, transesterification was modeled with 99% of the lipid entering the process converted to biofuel [52, 75]. The process loss modeled in this step is based on what is expected from a large-scale production facility [15, 39, 52, 74-77].

2.1.4 Recycling-Anaerobic Digestion

The baseline recycling process utilizes an AD for nutrient recovery and biogas generation from the LEA and whole biomass recovered from the filtration of the centrate in the dewatering step [52]. The biogas production of the AD system was modeled based on the microalgae composition in terms of volatile solids (VS) and total solids (TS), methane yield per gram of volatile solids (g-VS), and percent methane (CH₄) content in the biogas. A characteristic of 0.94 g-VS g-TS⁻¹ for whole biomass, and 0.90 g-VS g-TS⁻¹ for LEA was assumed and kept constant for all scenarios [75, 78]. The biogas yield from whole biomass was assumed to be 0.43 L-CH₄ g-VS⁻¹ at 67% CH₄, 0.80 L-CH₄ g-VS⁻¹ at 62% CH₄, and 0.25 L-CH₄ g-VS⁻¹ at 72% CH₄ for the baseline, optimistic, and conservative scenarios, respectively [78-80]. Similarly for the digestion of LEA, biogas yield and composition for the baseline, optimistic, and conservative scenarios were assumed to be 0.22 L-CH₄ g-VS⁻¹ at 59% CH₄, 0.31 L-CH₄ g-VS⁻¹ at 49% CH₄, and 0.14 L-CH₄ g-VS⁻¹ at 69% CH₄, respectively [75, 80-82]. It was assumed that all recovered biogas would be burned in an on-site combined heat and power unit. In describing the baseline performance of the AD, it was assumed that 76% of the nitrogen is recovered which includes a 5% volatilization loss [15, 80]. Phosphorus is assumed to be recovered with a 70% efficiency for the baseline scenario [83]. For the optimistic and conservative cases, nitrogen and phosphorus recovery via AD were assumed to be 85% and 60%, respectively [15, 80, 83].

2.2 Alternative Process Scenarios

Two alternative process scenarios were modeled and evaluated: a) the use of LEA as a co-product and b) hydrothermal processing of the biomass to bio-oil through HTL. The LEA co-product scenario provides further insight to claims made by previous TEAs in regard to the economic value of the LEA, and HTL represents a promising alternative processing technology due to the ability to process wet biomass and recover nutrients. For each of the LEA co-product and HTL scenarios, the baseline assumptions are used unless otherwise detailed.

2.2.1 Lipid-extracted Algae (LEA) Co-product

Analyses of the economics of biofuel production typically include discussion in regard to higher-valued co-products derived from the LEA to improve the cost of biofuel production [14, 18]. While the generation of revenue supplemental to that of biofuel through LEA co-products is economically advantageous, its implications on resource demand must be assessed. In this study an alternative scenario was modeled which considered using the LEA as a value added co-product. The LEA co-product scenario assumes all of the lipid-extracted biomass is removed from the process stream as a product after lipid extraction and used as aquaculture feed, and thus eliminating the AD system. It is assumed the minimal whole biomass recovered in the filtration of the centrate in the dewater step is added to the LEA product stream.

2.2.2 Hydrothermal Liquefaction

HTL is a technology currently being evaluated which breaks down biological matter into bio-oil and elemental components, providing the advantages of processing wet biomass and the partial conversion of proteins and carbohydrates to bio-oil [84-92]. The outputs of this process are bio-oil, biogas, nitrogen and potassium-rich aqueous phase, and precipitated phosphorus and sulfur [87, 93]. The modeled process replaces the extraction and the AD processes of the baseline production system.

118 The bio-oil yield from the process is assumed to be 50% based on recovery of the 30% algal lipid
119 content and 20% additional bio-oil through the conversion of carbohydrates and proteins [84-87, 93].
120 The percent phospholipid content was set to 0% because HTL strips the phosphates from any
121 phospholipids in the processing of the feedstock [84, 87]. The biomass caught by the filter in the
122 dewater process is sent into the HTL process. Nutrient recovery was assumed to be 75% for nitrogen,
123 with the remaining nitrogen being contained in the bio-oil, and 95% for precipitated phosphorus
124 recovery and processing [87].

125 **Table 1. Summary of primary system parameter input values for the five microalgae to biofuel production scenarios modeled**
126 **in this study with additional modeling parameters presented in the supplementary material.**

Parameter	Baseline	Optimistic	Conservative	LEA co-prod	HTL
Process Loss (%)	1	0.5	2	1	1
C:N:P Ratio	106:16:1	166:20:1	79:16:1	106:16:1	106:16:1
Hydrogen (%)	7.5	6	9	7.5	7.5
Lipid Content (%)	30	40	20	30	30
Phospholipids (%)	25	5	30	25	0
N Consumed by Microalgae (%)	99	100	98	99	99
Biomass Unharvested (%)	14.5	2.0	20.0	14.5	2.0
Biomass Unextracted (%)	10	5	15	10	0
Extracted Lipid Lost (%)	5	2	8	5	0
N Recovery (AD) (%)	76	85	60	0	66
P Recovery (AD) (%)	70	85	60	0	95
CH ₄ Production –Biomass (L-CH ₄ g-VS ⁻¹)	0.43	0.80	0.25	N/A	N/A
CH ₄ Production – LEA (L-CH ₄ g-VS ⁻¹)	0.22	0.31	0.14	N/A	N/A
CH ₄ in Biogas – Biomass (%)	67	62	72	N/A	N/A
CH ₄ in Biogas – LEA (%)	59	49	69	N/A	N/A

3. Results and Discussion

3.1 Total Resource Requirements

Mass balance calculations were performed for the five biofuel production scenarios, each at the renewable fuel production level of 10 BGY, to quantify the required nitrogen and phosphorus demands. A fuel production level of 10 BGY was selected based on a realistic contribution to the 2030 DOE renewable fuel goal of 60 BGY and represents a similar scale to other scalability assessments [32, 33]. Baseline results show for production of 10 BGY 167 million metric tonnes (Mmt) of biomass must be generated requiring 3.85 and 0.87 Mmt of nitrogen and phosphorus respectively. Results for the other scenarios are normalized to the baseline results and presented in Figure 2 with a table of results presented in the supplementary material. Water consumption was also calculated based on the hydrogen content of the grown biomass and represents <1% of total water demand compared to evaporation losses previously reported in the literature (details presented in the supplemental material) [25, 26].

Figure 2. Biomass, nitrogen, and phosphorus requirements for the 4 alternative scenarios to produce 10 BGY of biofuel, normalized to the baseline requirements of 167 Mmt biomass, 3.85 Mmt nitrogen, and 0.87 Mmt phosphorus.

The lower and upper bounds for nutrient requirements for large-scale microalgae production are illustrated through the optimistic and conservative results, with the baseline scenario portraying the expected resource demand from production that is realizable in the near-term. Over one hundred and fifty million metric tons of biomass will need to be grown in the baseline scenario to produce 10 BGY of fuel corresponding to a land area of 3.5 million hectares based on the assumed growth rate of 13 g m⁻² day⁻¹ [52]. This land requirement does not represent a resource constraint as concluded by previous assessments [26, 27, 94]. The total nitrogen and phosphorus needs for the optimistic scenario are approximately one-fourth those of the baseline scenario, with the conservative scenario requiring four times the nitrogen and three times the phosphorus compared to the baseline scenario. The large variation in nutrient demand can be attributed primarily to the range in efficiency of nutrient recovery in the AD. The LEA co-product scenario, characterized as the baseline scenario without AD, has roughly the same nutrient requirements as the conservative scenario. Alternatively, HTL has approximately half the required biomass production and nitrogen demand from the baseline, and a phosphorus requirement less than one-tenth of the baseline, similar to the optimistic scenario. The ratio of nitrogen input to phosphorus input is much higher in the HTL scenario because of the high nitrogen content in the bio-oil, an issue that necessitates further downstream processing [85]. The integration of HTL represents a promising technology based on nutrient recovery.

3.2 Scalability Assessment Based on Resource Availability

System scalability was assessed through a comparison of the total raw nutrient requirements for the various scenarios compared to current wastewater [95, 96] and fertilizer resource in the US [97], Figure 3. Previous growth studies have demonstrated nutrients for the cultivation of microalgae can be obtained from fertilizer or by utilizing a growth medium that already contains nutrients such as wastewater [33, 35]. Detailed calculations, assumptions, and tabulated results related to Figure 3 are provided in the supplementary material.

Figure 3. Scalability assessment: Biofuel productivity based on use of 100% of either US wastewater or fertilizer for the modeled scenarios. Error bars on the baseline scenario are representative of the optimistic and conservative scenarios.

The scalability assessment shows nitrogen and phosphorous requirements are a potential barrier to the scalability of microalgae biofuels. The nutrients available from wastewater correspond to a fuel production level of 3.8 BGY or 6% of the 2030 DOE fuel goal for the baseline scenario with none of the scenarios meeting the goal. Meeting a production level of 10 BGY would require 2.6 times the available wastewater in the US (based on the baseline scenario) illustrating wastewater to be a possible supplement, but not the ultimate source for nitrogen or phosphorous. The HTL scenario is the most promising with a production capacity of 14% of the 2030 DOE goal based on nitrogen availability.

Commercial fertilizer represents a viable nutrient source, but scaling microalgae systems will put significant strain on the US fertilizer market for the baseline scenario. The HTL and optimistic scenarios represent promising pathways in terms of nutrient requirements. Meeting a production level of 10 BGY would require 7.3% and 4.7% of the nitrogen fertilizer market and 1.6% and 4.3% of the phosphorus market, based on the HTL and optimistic scenarios, respectively. However, the optimistic scenario requires significant technological advancement from the current state while HTL has been demonstrated at the pilot plant level [40].

Results from the LEA co-product scenario illustrate the necessity for the recycling of nutrients. The nutrient requirements exceed the current resource and show that for significant levels of biofuel production, >10 BGY, nutrients from the LEA must be recycled. The recycling requirement limits the end use as a value added product. Results from the scalability assessment show that independent of scenario, nutrient management represents an important aspect of microalgae scalability.

3.3 Comparison to Previous Nutrient Assessments

A variety of microalgae based TEA and LCA studies have reported nutrient requirements for the cultivation of microalgae but have failed to include nutrient availability at large-scale in the analysis [7-21, 25, 35, 52]. Incomplete resource assessments have led to a large uncertainty in the current requirements for large scale production [7-9, 15, 32-35, 52]. Results from previous studies were normalized to the baseline units of this study, 10 billion gallons of fuel production annually from 167 Mmt of biomass. Normalized nutrient demand values reported in surveyed literature range by a factor of 10 from 2.3 Mmt of nitrogen and 0.68 Mmt of phosphorus [15, 52] to 24.5 Mmt of nitrogen and 3.5 Mmt of phosphorus [8, 35] as shown in Figure 4.

Figure 4. Results for (A) Nitrogen demand and (B) Phosphorus demand from various literature sources as compared to the baseline results of this study (black dotted line) at a fuel production level of 10 BGY.

The nutrient requirements in this study are 1.6 and 1.3 times the lowest values and 0.16 and 0.25 times the highest values reported in the literature surveyed for nitrogen and phosphorous requirements, respectively. Interestingly, when compared to the high productivity scenario from Pate et al. [33], the

most comparable results to this study, the baseline requirements are 63% and 105% of their results for nitrogen and phosphorus. The differences and similarities in results occur through a combination of factors, specifically that Pate et al. [33] only consider the growth phase for nutrient requirements, neglect all losses, and assume high algal productivity, each of which introduces uncertainty. Foundational assumptions in regard to nutrient availability also impact direct comparisons. Venter et al. [32] assume a nitrogen and phosphorous availability in wastewater that is 1.7 and 1.25 times higher than this study based on population and GIS assumptions. Compared to literature, the baseline results obtained in this study are similar with results from previous studies, falling between the high and low values reported. The large variance in previously reported results stem from differences in processing pathways and engineering process model fidelity. Results from this study are derived from an improved process model which describes a complete production system including recycling and system losses. Transparency in the modeling work performed and the high level of detail enables a more holistic understanding of the nutrient requirements with the various scenarios used to bound the nutrient requirements at scale.

3.4 Sensitivity Analysis

A sensitivity analysis was performed to illustrate which process parameters have the greatest effect on resource demand and to ultimately guide future research. The sensitivity analysis was performed by independently varying each system parameter by $\pm 20\%$ from the baseline and recording the nitrogen and phosphorus requirements and utilizing an analysis of variance to estimate t-ratios for each input parameter. Results from the sensitivity to process parameters, in order of greatest impact on resource requirements, are presented in Figure 5. Results were analyzed using a one tail distribution with a 95% confidence interval, resulting in a critical t-ratio of 2.1. The critical t-ratio provides the boundary through which system parameters are deemed as sensitive or non-sensitive. The parameters whose t-ratio magnitude is above the critical, and thus whose bar extends beyond the confidence

interval in Figure 5 were deemed sensitive. Although twenty-four system parameters were varied, the ten parameters with the highest sensitivity based on t-ratio were included in Figure 5.

Figure 5. One-tailed results from sensitivity analysis of system parameters for (A) Nitrogen requirement and (B) Phosphorus requirement. Numbers in parenthesis correspond to baseline value followed by t-ratio; critical t-ratio equal to 2.1. Only the top 10 sensitive variables presented with additional results presented in supplementary material.

The two parameters whose variation has the greatest impact on system nutrient demand are the nitrogen and phosphorus recovery rates of the AD. It must be noted that AD technology has matured such that only minor increases in N and P recovery can be expected. However, advancement in nutrient recovery by use of an alternative technology such as HTL, could dramatically impact the scalability. The next group of parameters most capable of driving down resource demand are those describing the composition of the microalgae strain. This demonstrates that the microalgae strain characteristics including C:N:P ratio, lipid content, phospholipid content, and carbon content must be thoroughly understood and even optimized through synthetic biology or other means for efficient nutrient use in microalgae growth and lipid production. Resource requirements for large-scale microalgae production can be reduced through technological improvements affecting these sensitive system parameters.

Conclusion

A detailed and modular engineering system model was developed and used to determine total system nutrient (nitrogen and phosphorus) requirements for five microalgae to biofuel production scenarios at a production level of 10 BGY, corresponding to a significant contribution toward the DOE 2030 goal. Optimistic and conservative process scenarios were modeled in an effort to bound the nutrient requirements for large-scale microalgae production with a baseline scenario intended to represent a near-term commercial system. Baseline nutrient requirements for attaining the full DOE 2030 goal dramatically exceed the nutrients available in wastewater and are equivalent to the current fertilizer consumption in the US. Utilization of wastewater as the sole source of nutrients limits microalgae biofuel production to 3.8 BGY based on the baseline scenario. The nutrient demand for large-scale production requires nutrients to be recovered from the LEA, and thus LEA cannot be used as an economically beneficial co-product. The HTL scenario shows that it has significant advantages over the baseline scenario, including lower biomass production and nutrient requirements. Sensitivity analysis shows that resource demand can be impacted through improvements in nutrient recycling and microalgae strain characteristics. Results highlight the importance of nutrient management and the limited impact integration with wastewater systems has on microalgae requirements at large-scale.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version.

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