# High-Alkalinity Algal Cultivation with Direct Air Capture: An Economic Feasibility Analysis

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# Abstract

Weather variability and $CO_2$ supply costs remain key barriers to the commercial viability of algal biofuel production. Recent experimental work has demonstrated that the algae *Chlorella* sp. strain SLA-04 achieves high productivity in extreme alkaline growth media (pH > 10), where the solution chemistry enables direct capture of atmospheric $CO_2$, eliminating the need for costly $CO_2$ sparging. The extreme alkaline medium also provides resistance to microbial contamination and culture crashes. Despite these promising experimental results, the commercial-scale economic and environmental implications of this cultivation approach have not yet been assessed. Here we present the first integrated Techno Economic Analysis (TEA)/Life Cycle Analysis (LCA) of high pH-high alkalinity production, driven by 500 stochastic simulations of 20-year weather and market conditions. We compare four SLA-04 cultivation scenarios against a baseline strain cultivation scenario with *Nannochloropsis oceanica* and sparged $CO_2$. These scenarios also include the first incorporation of Trona, a naturally occurring carbonate mineral and the primary domestic source of bicarbonate in the United States, into our TEA/LCA framework as a low-cost alternative to commercial $NaHCO_3$ for establishing the high-alkalinity growth medium. Our results indicate that the SLA-04-Trona scenario reduces operating expenses by 60% per gallon relative to the baseline, and SLA-04 exhibits lower production variability across all seasons. The high pH-high alkalinity cultivation method also reduces the carbon intensity of algal biofuel by approximately 40%, achieving values below corn-based ethanol. These findings provide the first quantitative evidence that high pH-high alkalinity cultivation can substantially improve both the economics and environmental footprint of commercial-scale algal biofuel production.

# 1 Introduction

Though the electrification of the transportation sector is well underway, liquid fuel will continue to be necessary for air travel, marine transport and other hard to electrify sectors well into the future (1). Crude oil provides the vast majority of liquid fuel today (2) yet presents many direct environmental hazards (notably acute and chronic aquatic toxicity, carcinogenicity) (3,4) and serious indirect hazards via emissions of pollutants, including greenhouse gases. Algae-based hydrocarbons are a potential petroleum alternative that can be refined into biofuels and a variety of other products, including some not available from petroleum refineries (e.g., organic meal/livestock feed, bio-carbon) (5). While the costs of cultivating, extracting, and processing algae into a usable fuel are declining, there has been limited progress at the commercial scale over the last decades to make it a commercially competitive alternative to fossil fuels.

Outdoor open raceway ponds (ORPs) are currently considered the least cost-intensive and most scalable method of large scale algae cultivation, with capital cost estimates averaging $75,000 per acre (6,7). In terms of total investment, only the cultivation facility with 5000-wetted acres of pond area (a commonly analyzed unit) could cost $200,000,000 before investing in refinery infrastructure or accounting for operational expenses. These costs must be balanced by a steady revenue stream based mostly on algae production. Typical algal strains receiving attention from the research community have average growth rates of 7 to 16 g $m^{-2}$ $day^{-1}$ when cultivated in ORPs (8), with the productivity range varying significantly, often as a result of weather variability, especially variations in temperature and solar irradiance (8,9). Consequently, algal productivity in ORPs is subject to considerable seasonal and interannual variability. In addition, a range of microorganisms have been observed to cause algal culture crashes (8,10–13). Deviations from expected weather conditions (e.g., cold snaps, cloudy periods) and microbial contamination events therefore pose risks to the financial stability of an algae producer or integrated biorefinery (which spans from cultivation to conversion). However such considerations were not included in previous analyses, most of which have largely focused on average productivity (7,14–17). Given that revenue and cost instability pose significant risks to any investment, particularly those that are financed and therefore have firm debt service obligations, highly variable algae productivity can undermine investor confidence in the potential of an algae producer, making it more difficult and/or costly to raise the capital required.

Previous studies have focused on reducing capital and operational expenses, as well as improving process efficiencies to address these concerns, with carbon delivery receiving considerable attention over the past 10 years (18). Cultivation systems without $CO_2$ sparging are rarely considered, as natural diffusion of atmospheric carbon into the water column (even with enhanced mixing) can quickly become a limiting factor for algae growth (19). Often, carbon is delivered to the ponds as $CO_2$ via sparged flue gas from thermal power generation, a common carbon source due to its relatively high $CO_2$ concentration and the benefits of fixing carbon from fossil fuel combustion (19,20). Other literature describes research related to optimizing carbon delivery, its impact on algae growth, and potential alternative $CO_2$ sources, such as off-gas from an oil well, or commercial-grade $CO_2$. The costs of $CO_2$ collection, transportation, and delivery to ORPs comprise 10-20% of the overall capital and operating expenses of algae production (7,16,17). Furthermore, situations that involve reliance on flue gas as a $CO_2$ source restrict siting options and tethers algae cultivation to fossil fuel consumption. Recent research suggests that there may be a viable alternative method for providing inorganic carbon to the algae cultivation process. The use of high pH-high alkalinity growth media in ORPs can provide a high concentration of inorganic carbon while increasing the rate of mass transfer of $CO_2$, which supports elevated levels of algae productivity (21). In particular, *Chlorella* sp. strain SLA-04, is highly productive in high pH-high alkalinity conditions, often exhibiting higher growth rates than those achieved by other algal strains of common commercial interest (21). A cultivator utilizing high pH-high alkalinity cultivation (via bicarbonate chemistry) could decrease production costs by avoiding the requisite $CO_2$-sparging, remove related siting constraints, and in doing so generate reductions in the carbon intensity of algal biofuels or other algae-based products.

Such algae production may be attractive from a commercial standpoint, however, to our knowledge, no techno-economic analysis/life-cycle analysis (TEA/LCA) has been published assessing the potential of high pH/high alkalinity algal cultivation processes using SLA-04. This research aims to characterize the potential of a commercial-scale integrated biorefinery that uses high pH-high alkalinity ORPs to make algal biofuel production more cost competitive by building on an existing TEA/LCA modeling platform (9,22). The model is expanded to include multiple inorganic carbon source options and various forms of carbon delivery, including sparging of industrial flue gas (the base case) and direct air capture driven by a high pH/high alkalinity growth medium created using either commercial $NaHCO_3$, or Trona, the mineral resource that is the primary supply of bicarbonate in the United States (23). Pond temperature and SLA-04 productivity are modelled using stochastically generated weather conditions (temperature, irradiance, relative humidity, and wind speed) to characterize the risk that extreme weather, or prolonged periods of adverse weather, may reduce algae production. Price data for the primary product of this analysis, biodiesel, are also stochastically generated to incorporate consideration of market price variability. Consideration of stochastic algae production and financial conditions, often neglected in TEA models, provides for a more robust analysis of the economic potential of a product dependent on environmental conditions. Further analysis is done to evaluate the financial implications of the California Low Carbon Fuel Standard (24), which provides credits for low carbon fuel production. Results from these analyses provide useful insights for researchers interested in the potential for new process configurations to improve the commercial potential of algal biofuels/bio-products, as well as private-sector actors considering alternative products and production processes.

## 2 Methods

The overall model framework for an algal biofuel production facility is shown in Figure 1. The figure depicts the scenarios considered in the manuscript and the overall TEA/LCA process. The system production, costs and revenues are simulated using five hundred 20-year timeseries of synthetically generated market price and hourly weather conditions at Vero Beach (Florida), one of the sites of the Algae Testbed Public-Private Partnership (8). The weather data are produced stochastically as in Kleiman et al. (22) and are used as inputs to the pond temperature model and fitted growth model, which produce 40,000 three month periods (quarters) of simulated pond productivity.

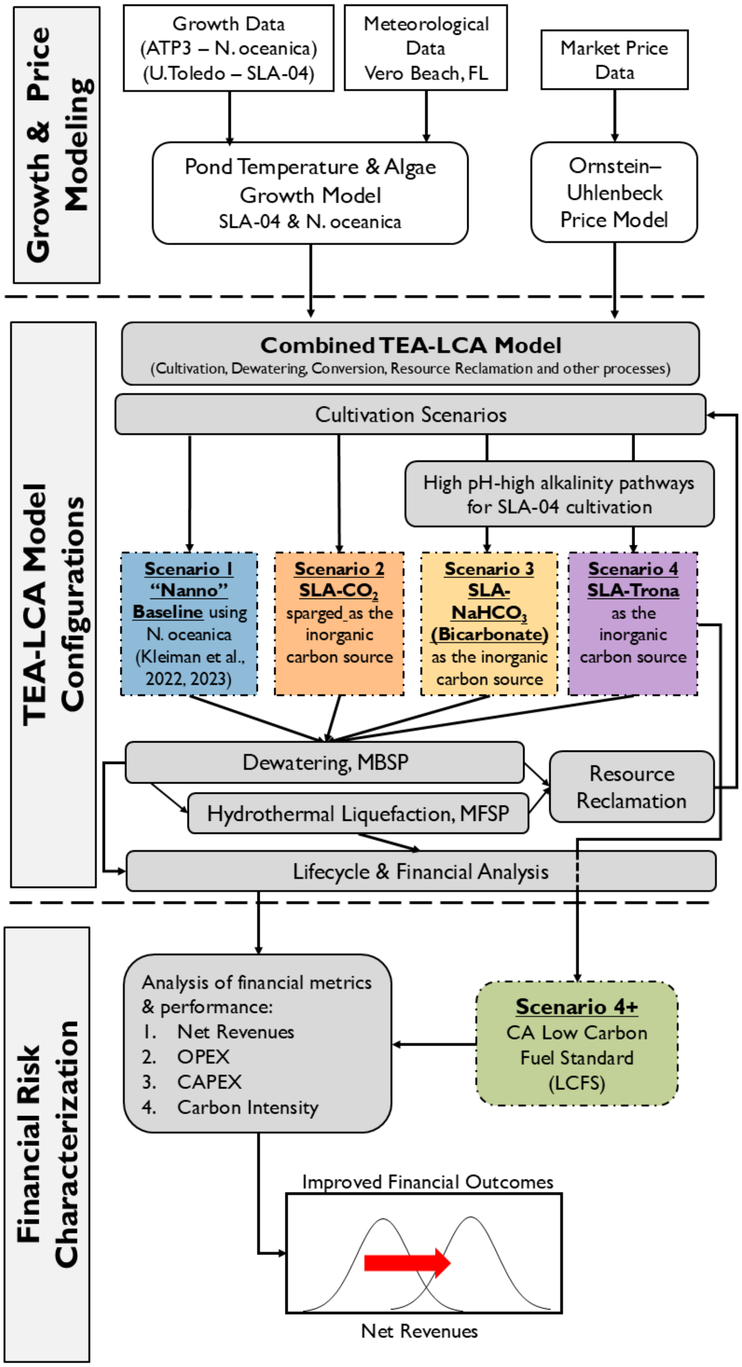

Figure 1: Graphical depiction of model framework of the Techno-Economic Analysis / Life Cycle Analysis Model including the multiple scenarios considered in this study.

The TEA/LCA modeling framework analyzes system performance over a range of possible plant configurations, economic regimes, and produces estimates of the productivity, minimum biomass and fuel selling price (MBSP & MFSP), and other key metrics of interest within a reasonable range (14,25). The TEA/LCA model used in this study (Figure 1) is built upon existing models developed by Kleiman et al. (22) who assessed the influence of weather variability on the financial viability of an algae biorefinery. The TEA includes multiple available dewatering and conversion options for the production of algal biofuel which have been applied under both average weather conditions and stochastic weather conditions that vary at an hourly time step. Please see Kleiman et al. (22) for additional details on the methods.

After cultivation, the algae slurry is dewatered via a settling tank, centrifugation, and membrane separation, then converted to biofuel via hydrothermal liquefaction. At a productivity of 15 g $m^{-2}$ $day^{-1}$, annual production would be approximately 8.16 million gallons of fuel for a gross production of 163.2 million gallons over the proposed 20-year plant lifetime. Financing assumptions were 4% interest rate, 10% return on investment, 10% discount rate, and a 21% tax rate. Biofuel prices are stochastically generated for each quarter via an Ornstein–Uhlenbeck model, similar to that used in previous research (22). Revenue estimates are aggregated to a quarterly time step.

The primary changes made to the TEA/LCA modeling framework pertain to the changing production configurations for cultivation of SLA-04 (21). The biggest production change is the high pH-high alkalinity solution with costs estimated for both Trona and commercial bicarbonate. Strain specific characteristics pertaining to algae growth and temperature dependence are included to accurately model productivity under different weather conditions. The changes made to the TEA/LCA model are described in further detail below.

### 2.1.1 High pH-High Alkalinity Cultivation

The new cultivation option built into the TEA/LCA model for an integrated biorefinery allows for the cultivation in a high pH high alkalinity medium using commercial $NaHCO_3$/$Na_2CO_3$ or Trona as the inorganic carbon source. As the unrefined mineral precursor for $NaHCO_3$, Trona presents potential economic and environmental benefits as it possesses the lowest greenhouse gas footprint and embodied energy of the considered carbon sources. However, it has only been used in algae cultivation in limited settings (26). As Trona is not available on a commercial scale, the cost of Soda Ash was used as a substitute. Thus, Trona price was estimated as the 5-year average price (150$/Short ton) (23).

To compare changes in the life-cycle costs by substituting carbon sources, values for the greenhouse gas footprint and the embodied energy content of each source are required. The values for bicarbonate and industrial $CO_2$ captured from unconcentrated flue gas are existing model parameters (22). Trona, however, had no published values for its embodied energy costs or associated greenhouse gas footprint. Its values are estimated using publicly available data from

US soda ash producer and Trona extractor, Ciner Resources in Green River, Wyoming. This producer was analyzed as they had the clearest data reported to the EPA, mandated public reporting to Securities and Exchange Commission (SEC), and the most straightforward operations among the soda ash producers in the United States, as they produce no other products and run all their operations on natural gas. Greenhouse gas emission data reported to the EPA (27) and the company's annual report filed with the SEC (28) are used to compute carbon intensity and embodied energy based on the total Trona ore production, emissions, and energy consumption reported in 2020 (Table 1).

Table 1: TEA/LCA Model parameters for different carbon sources

| *Carbon Source* | *Cost Per unit ($/kg)* | *Carbon intensity (g/kg)* | *Embodied Energy (kwh/kg)* |
|---|---|---|---|
| $CO_2$ (Base case) | 0.042 (29) | 0.818 (30) | 2.3 |
| Trona | 0.167 | 97.18 | 0.00053 |
| $NaHCO_3/Na_2CO_3$ | 0.55 (31) | 66.35 | 0.3 |

### 2.1.2 Estimating Carbon Demand

Carbon demand is estimated separately for the two cultivation scenarios, one for sparged flue gas ($CO_2$) in a neutral pH environment and one for a high pH-high alkalinity solution. In the case of sparged flue gas, carbon required is estimated via a mass balance based on the algae grown, consistent with previous publications of this model and other analysis (7,16,17,22,32). Algae is assumed to be 55% carbon by weight, and system losses are assumed to be 15% of the carbon sparged into the pond (7,19). Thus, per gram of algae produced, 2.37 g of $CO_2$ from flue gas is required.

In the second case, solution demands are estimated stoichiometrically for either the quantity of $NaHCO_3/Na_2CO_3$ or Trona necessary to create the solution, based on a desired pH and alkalinity. In this analysis, the media was set to an initial alkalinity of 119 mEq, and a pH of 10.1. These values were selected as they resulted in the highest growth rates in experiments reported in Vadlamani et al. (2019) (21). A considerable quantity of $NaHCO_3$ for the 5000 wetted acre pond area cultivation facility is required to create the initial solution, approximately 43 thousand metric tons, and this cost is considered a capital expense. Refer to supplementary materials for more information.

### 2.1.3 Biophysical Growth Model Fitting and Validation

#### Experimental Growth Data

To model growth of SLA-04 growth in high pH-high alkalinity conditions, model parameters are fitted to experimental growth data from SLA-04 growth experiments conducted at the University of Toledo in 2021. The fitting data are from two identical above-ground ponds (which had a surface area of 0.18 $m^2$, an operating volume of 20 L, and operating depth of 20 cm), which were operated from June 25 to September 9 in a greenhouse at the University of Toledo. During this period there was considerable temperature variability recorded within the ponds (11.3 to 39.7 $^oC$) and highly variable cloud cover (0-97%, average 29%). The two ponds were fitted with temperature probes that recorded temperatures every 5 minutes. The data from each probe is averaged together and averaged hourly for use as the input for pond temperature in the biophysical growth model. This prevents error propagation from modelling pond temperature, as the model is not designed to predict the temperature of above-ground ponds. Irradiance data for the site was collected from Solcast at a half-hour timestep and summarily aggregated to the hourly timestep. Irradiance is uniformly reduced by 10%, to incorporate the opacity of the greenhouse. Harvesting was conducted by volume (80% of the total) once per week with the remaining algae used to reseed the ponds. In practice this led to some variability in the experimental data as post-harvest concentration would be +/- 15% of what was expected based on the harvesting procedure. Depending on the harvest day, pre- and post-harvest concentration would be reported, or just post-harvest concentration. Following a harvest, solution alkalinity was returned to its original concentration by adding bicarbonate as necessary.

#### Growth Model Fitting and Validation

The growth model is configured to match the pond dimensions and operating conditions described above. Initial model parameters for algal growth are those listed in Table S1 in the Supplementary Material for *Chlorella sp.*, which is of the same genus as SLA-04. Existing experimental evidence suggested that these two strains prefer similar temperature conditions (21), and there is no evidence to suggest that the optical density regression or dark loss respiration would be distinct for SLA-04. As such, saturation light intensity, the light intensity at which the algae begin to experience photo-inhibited growth, was increased to optimize model fit, which is achieved at 360 $W/m^2$. This is within the range (230 – 480 $W/m^2$) reported for a variety of different algae and is justified by the high productivity observed in the experimental dataset, which exceeds what is often achieved in cultivation of *Chlorella* sp. (8,33–35). Refer to Supplementary Materials for additional information on the biophysical growth model.

Figure 2 displays the fit between the experimental concentration at harvest versus the modelled concentration at harvest using the parameterized biophysical growth model. The biophysical growth model generates concentrations that are highly correlated ($R^2$ = 0.78) with observed data. Moreover, this represents an improvement between observed and modeled concentrations ($R^2$ = 0.55) in the growth model used in previous iterations of this TEA/LCA framework (9).

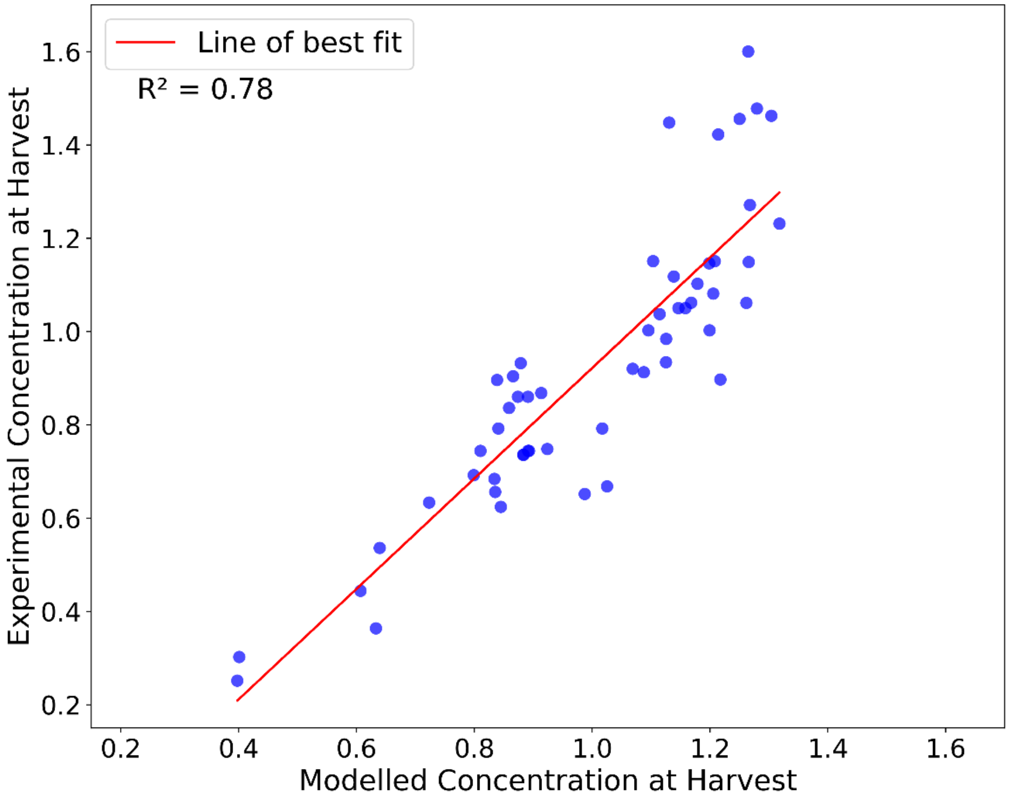

Figure 2: Experimental and modelled concentration data using the updated biophysical growth model for pond concentration (g/l) at harvest for SLA-04.

## 2.2 Low Carbon Fuel Standard

High pH-high alkalinity biofuel production without any $CO_2$ sparging involves direct air capture (DAC) of atmospheric $CO_2$. Thus, it is a technology to mitigate anthropogenic climate change and may be eligible for related market incentives, such as the California Low Carbon Fuel Standard (LCFS). The LCFS is a market-based regulatory program designed to reduce the carbon intensity of transportation fuels sold in California. The market operates by setting a cap that decreases on an annual basis for the carbon intensity (g $CO_{2eq}$/MJ) of a fuel type (*e.g.*, diesel) and issues credits to producers relative to the baseline carbon intensity per metric ton of $CO_{2eq}$ avoided. If the fuel produced is below the carbon intensity standard, then that producer earns credits, which can be banked by producers for future use or sold to producers with a carbon intensity above the standard. The TEA/LCA modeling framework incorporates consideration of this potential revenue stream to compute the improvement in the modeled facility's financial results. Since the program overhaul in 2016, credit price has ranged from \$110-\$220/MT $CO_{2eq}$. \$252.53/MT $CO_{2eq}$ is the credit price cap set by the California Air Resources Board (CA ARB) (24). This analysis estimates the potential revenue to be earned by selling all the credits generated quarterly by the biorefinery at the average price (since 2016) which is \$150/MT $CO_{2eq}$. This is also the price at which credits begin to be released from the CA ARB market reserve pool. On a per gallon basis this translates to a \$1.02 credit and therefore is among the largest of regulatory schemes in the United States.

# Results

All results are computed on the basis of a functional unit of a 5000 wetted acre pond facility over a 20-year project horizon. We first compare the biomass productivity and variability between *N. oceanica* and SLA-04, then examine the differences in operating expenses, carbon intensity, and net revenue across the different scenarios. Finally, we evaluate the additional financial impact of incorporating LCFS credits under the SLA-Trona-LCFS scenario.

## Reduction in Variability, Costs and Emissions

The biomass productivity per square meter of pond surface varies by quarter (g $m^{-2}$ $day^{-1}$) across Q1 (Jan-Feb-Mar), Q2 (Apr-May-Jun), Q3 (July-Aug-Sep) and Q4 (Oct-Nov-Dec) for both *N. oceanica* and SLA-04 (Figure 3). Across all quarters, model results indicate that SLA-04 will produce nearly double the quantity of biomass relative to *N. oceanica*, the strain studied in (22), though the modelled average daily productivity of 12.1 g $m^{-2}$ $day^{-1}$ was lower than the experimental average of 18 g $m^{-2}$ $day^{-1}$ for SLA-04 (21). Productivity trends are similar for both strains with the highest productivity in Q2 (late spring/early summer), followed by Q1 and then Q3, with the lowest productivity observed in Q4, which roughly corresponds to the temperature variations, with higher temperatures supporting greater biomass growth. The Coefficient of Variation (CoV, defined as the ratio of the standard deviation and the mean $(\sigma/\mu)$) was calculated for each strain for each quarter to examine and compare the variability in productivity. A seasonal pattern inverse to productivity emerges for the CoV, which is greatest in Q3 and Q4, and smallest in Q2 and Q1. Additionally, the CoV for SLA-04 is lower than the corresponding seasonal value for *N. oceanica* for all quarters. Using this modelling approach, the minimum biomass selling price

(MBSP, computed as the biomass price required for the project to break even after accounting for all capital, operating, and financing costs) for the SLA-Trona scenario is $705 per ton. This MBSP is $59 greater than the estimate in the 2023 State of Technology (SoT) report (36), however the annual average productivity of 12.1 g $m^{-2}$ $day^{-1}$ is lower than the standard of 16.7 g $m^{-2}$ $day^{-1}$ used there in. If productivity is assumed to increase to an average of 25 g $m^{-2}$ $day^{-1}$, a target set for goals for future "Nth-plant" scenarios in the 2019 SoT (20), the MBSP for the SLA-Trona scenario decreases to $342 per ton. At the average experimental productivity of SLA-04 of 18 g $m^{-2}$ $day^{-1}$ (21), the MBSP is predicted to be $472 per ton.

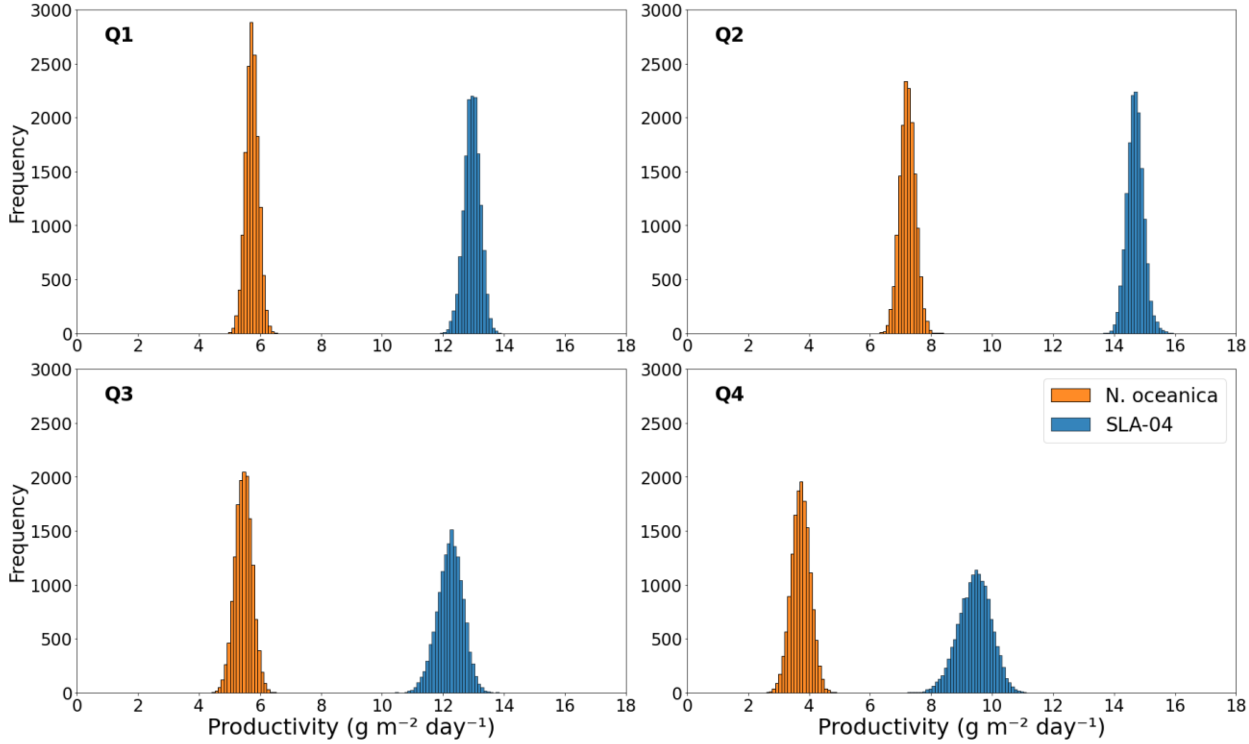

Figure 3: Quarterly productivity of biomass per square meter of pond surface area for SLA-04 and *N. oceanica*.

Multiple cultivation scenarios were considered using the TEA/LCA modeling framework. The baseline scenario considered in this modeling framework is the cultivation of *N. oceanica* in a neutral pH system (henceforth referred to as the “Nanno” or “baseline” scenario). The second scenario developed is cultivation of the SLA-04 strain using sparged $CO_2$ (henceforth referred to as the “SLA-CO2” scenario). The third scenario incorporated is cultivation using SLA-04, but with consideration and incorporation of direct air capture, with sodium bicarbonate serving as the inorganic carbon source (henceforth referred to as the “SLA-NaHCO3” scenario). The fourth scenario considered is the same as above, but Trona is the inorganic carbon source (henceforth referred to as the “SLA-Trona” scenario). The last scenario considered is one in which the SLA-Trona scenario is used plus the CA LCFS, which incorporates an accounting of the economic benefits ascribed to the direct air capture approach (henceforth referred to as the “SLA-Trona-LCFS” scenario).

Figure 4 represents the changes in the net present value (NPV) of lifetime capital and operating expenses of the integrated biorefinery normalized by lifetime biofuel production (59 million gallons under Nanno and 132 million gallons under SLA-04), thus accounting for the difference in production levels between *N. oceanica* and SLA-04 across multiple scenarios. Using a bicarbonate- or Trona-based solution to drive atmospheric mass transfer of carbon to support algae growth is a lower-cost method of delivering $CO_2$ compared to the baseline Nanno scenario (Figure 4). When considering total expenses (capital and operating costs), the SLA-Trona scenario achieves a cost of \$3.1/gallon compared to \$6.9/gallon for the Nanno baseline, representing a 55% reduction in total per-gallon expenses over the project lifetime. Utilizing Trona in the cultivation medium also leads to total operating expense savings of 0.39 \$/gallon or a 60% cost reduction across the lifetime of the integrated biorefinery compared to the baseline Nanno scenario. This represents a conservative estimate of the difference between $CO_2$ sparging in the base case and DAC in the SLA-scenarios since the model assumes a comparatively lower estimate of $CO_2$ system losses. However, the total capital cost is increased, by approximately \$20 million to purchase bicarbonate or Trona to establish the cultivation medium. This is offset somewhat by the decrease in pond installation cost as previous $CO_2$ delivery and sparging-related components are no longer necessary (pumps, pump heads and related pond infrastructure). This leads to additional cost savings in reduced electrical demand for pond mixing. Furthermore, the pond cost for the SLA-Trona and SLA-NaHCO3 scenarios is an overestimate, as the decrease in concrete required (related to the components above) is not accounted for. The cost of Trona is also likely overestimated, as Trona is not sold at commercial scale, and the price of soda ash used in this study reflects an added value of additional refining not required for Trona.

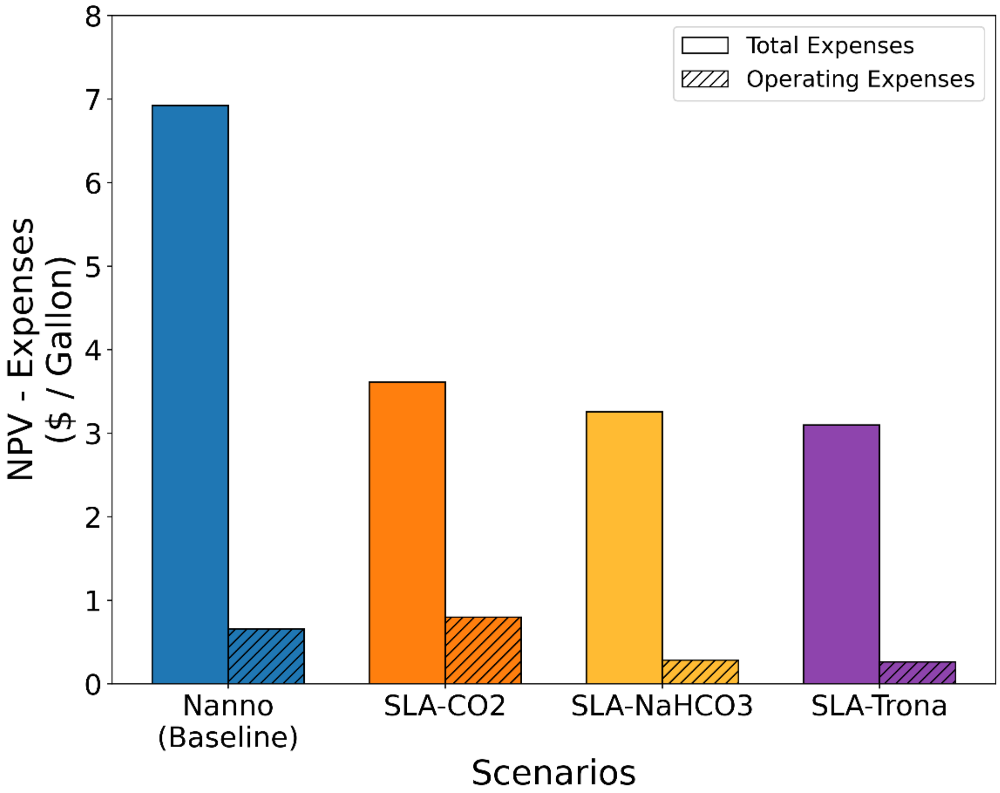

Figure 4: Net Present Value (NPV) of total capital and operating expenses over the project lifetime for each model configuration, normalized by total biofuel production. The solid and hashed bars denote the NPV of total capital and cumulative operating expenses (OPEX) respectively.

The estimated carbon intensity ($CO_{2eq}$ per mega Joule (MJ)) for the different cultivation scenarios represents the amount of carbon dioxide emissions (global warming potential) produced per unit of energy generated. Overall, all cultivation methods have a lower global warming potential than using fossil-based diesel fuel (Figure 5), which emits 94.7 g $CO_{2eq}$ / MJ (California Air Resource Board, 2021). Algae cultivation scenarios utilizing bicarbonate or Trona also exhibit a reduced global warming potential by ~40% relative to the Nanno scenario cultivation utilizing $CO_2$, a valuable improvement as it relates to eligibility for policy incentives. Under the LCFS, this improvement can be directly translated into revenue. At a price of $150/MT $CO_{2eq}$, decreasing the global warming potential by 27g $CO_{2eq}$/MJ, the difference between Nanno and SLA-Trona scenarios, is worth an additional $0.004/MJ ($ 0.48/GGE) of fuel produced. In this analysis, only the SLA-Trona scenario is modelled with the additional LCFS revenues as the SLA-Trona scenario achieves the highest quarterly revenues, as seen in Figure 6. This scenario is denoted as SLA-Trona-LCFS. Averaging across runs, the LCFS generates $1.375 million in revenue per quarter when biofuel is produced via the SLA-Trona scenario.

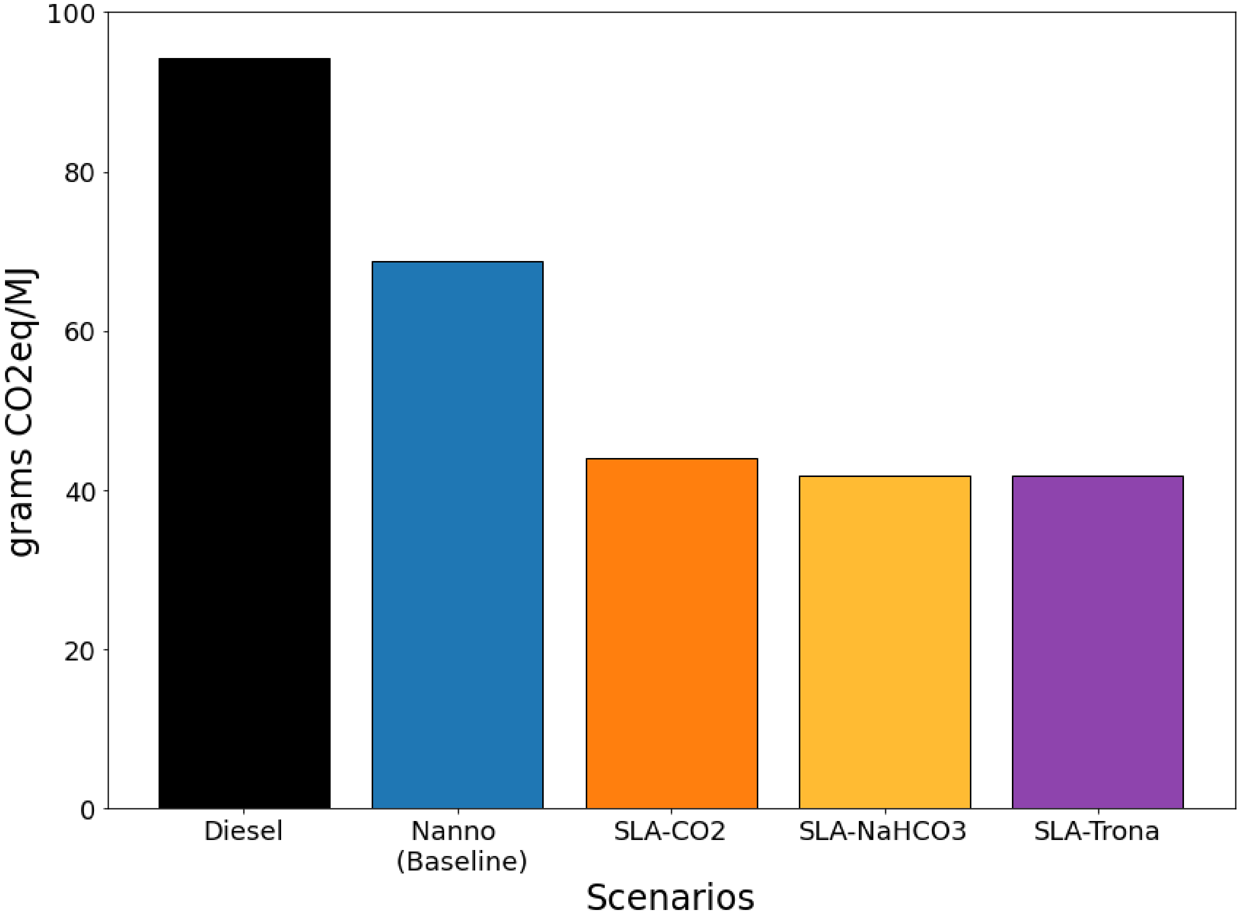

Figure 5: Carbon Intensity in grams $CO_{2eq}$/MJ for diesel, Nanno, SLA-CO2, SLA-NaHCO3 and SLA-Trona scenarios.

## Net Revenue Improvements Across Scenarios

Quarterly net revenues from the modelled quarterly productivity for the five different scenarios vary significantly across the 500 simulations of growth and price data (Figure 6). While the mean net revenues in all scenarios are still somewhat negative, the TEA/LCA model shows that the revenues from all four of the SLA-04 cultivation scenarios in a high pH-high alkalinity environment exceed the net revenues in the baseline cultivation scenario. Of the SLA-04 scenarios, the SLA-CO2 configuration outperforms the baseline (Nanno) scenario significantly but still loses $5.5 million per quarter on average. Both high pH-high alkalinity configurations using $NaHCO_3$ or Trona achieve greater improvements; the SLA-Trona configuration achieves an average quarterly net revenue of $-3.6 million and the SLA-NaHCO3 configuration returns $-4.15 million.

The best-case financial scenario is the SLA-Trona-LCFS, which exhibits positive net revenues in more than a third of total realizations. When the LCFS credits are included, there is a significant improvement in quarterly net revenue, returning on average $-2.19 million per quarter when applied to the Trona configuration. The greatest revenue shortfalls occur in Q3 and Q4 as these periods experience the lowest productivity, consistent with results in Kleiman et al. (2021).

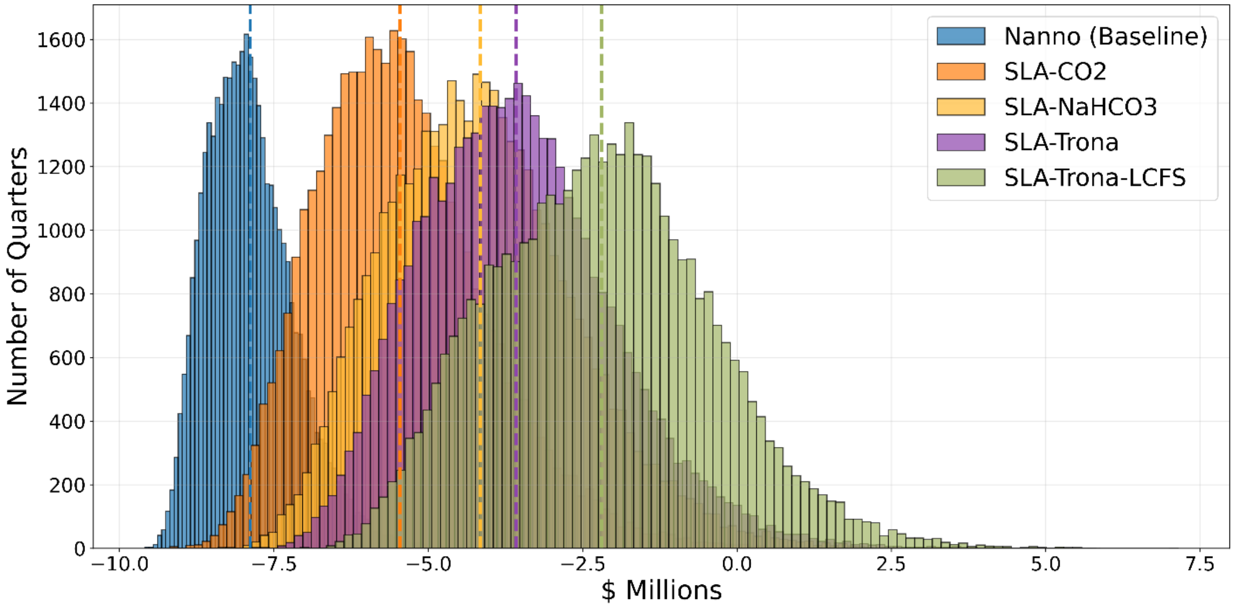

*Figure 6: Quarterly net revenues for an integrated refinery cultivating algae using multiple scenarios. The dotted horizontal lines denote the mean quarterly net revenues for each scenario.*

# Discussion

## Financial Competitiveness of the High pH-High Alkalinity Scenario

The SLA-Trona scenario achieves a 60% reduction in operating expenses per gallon of biofuel ($0.39/gallon savings) relative to the baseline Nanno scenario. This is driven primarily by eliminating $CO_2$ sparging costs that typically comprise 10-20% of total production expenses (7,16,17). Additional savings are realized through reduced electrical demand for pond mixing (15% reduction) and the elimination of $CO_2$ delivery infrastructure. These savings are partially offset by the ~$20 million capital expense of establishing the alkaline cultivation medium, though this cost is likely overestimated in this study, as the soda ash price used as a Trona-proxy reflects refining costs not applicable to raw Trona.

The minimum biomass selling price (MBSP) for the SLA-Trona scenario is $705 per ton at the modeled average productivity of 12.1 g $m^{-2}$ $day^{-1}$, which is only $59 per ton above the 2023 State of Technology benchmark despite a lower productivity assumption (12.1 vs. 16.7 g $m^{-2}$ $day^{-1}$) (36). At the average experimental productivity of SLA-04 (18 g $m^{-2}$ $day^{-1}$ (21)), the MBSP decreases to $472 per ton, and at the widely cited target productivity of 25 g $m^{-2}$ $day^{-1}$ (20), MBSP reaches $342 per ton. These values indicate that cultivation of SLA-04 is competitive with existing benchmarks and that even modest productivity improvements could substantially improve financial viability.

The most favorable financial scenario, SLA-Trona-LCFS, achieves positive quarterly net revenues in more than one-third of the 500 stochastic realizations, with an average quarterly net revenue of $-2.2 million per quarter. While negative on average, this represents a substantial improvement over the baseline Nanno scenario with an average loss of nearly $8 million per quarter.

## Reduced Production Risk

Beyond average cost improvements, the high pH-high alkalinity scenario reduces production variability, a consideration largely absent from prior TEA-LCA studies that rely on average productivity assumptions. The Coefficient of Variation (CoV) for SLA-04 productivity is lower than that for *N. oceanica* productivity across all quarters, indicating more stable biomass output under variable weather conditions. This reduced variability is attributable to the greater resistance of SLA-04 to microbial contamination at the extreme pH conditions. SLA-04 cultivated in experimental ORPs has not experienced culture crashes over a two-year observation period (21), a notable contrast to the crash events documented for freshwater species at neutral pH (8,10,11).

Reduced production variability has direct financial impacts that extend beyond the effect on average revenues. Lower revenue volatility improves debt service coverage ratios, reduces the cost of capital, and strengthens the overall business case presented to project finance investors and lenders. As modelled here, SLA-04 exhibits lower production variability than not only other algal strains of commercial interest, but also agricultural biofuel feedstocks such as corn and soybeans (9). This positions high pH-high alkalinity algae cultivation favorably among other biofuel scenarios in terms of investment risk.

## Implications of Decoupling from $CO_2$ Infrastructure

A significant advantage of the high pH-high alkalinity approach is the elimination of dependence on concentrated $CO_2$ sources. Conventional algae cultivation using sparged flue gas effectively tethers production to fossil fuel infrastructure, constraining siting to locations proximate to power plants or other large emitters and creating a long-term carbon source risk as these facilities face decommissioning pressures from decarbonization policies and competition from renewable energy (7). Expanding $CO_2$ pipeline infrastructure to serve algae facilities at alternative locations would likely be cost prohibitive, and existing pipeline networks are limited primarily to Texas and adjacent states (37). The high pH-high alkalinity scenario eliminates these constraints entirely, allowing siting decisions to be driven by climate suitability, land cost, and market proximity rather than $CO_2$ availability.

This decoupling also improves the carbon intensity profile of the produced biofuel. The SLA-Trona scenario reduces global warming potential by approximately 40% relative to the Nanno baseline, achieving a carbon intensity below that of corn-based ethanol (45.8 g $CO_2$eq/MJ (38)). This improvement positions algal biofuels produced via the high pH-high alkalinity scenario competitively within the broader landscape of low-carbon transportation fuels, particularly for hard-to-electrify sectors such as aviation and marine transport. The decreased carbon intensity of the high pH-high alkalinity scenario also creates tangible value in jurisdictions where carbon is priced. Under the California Low Carbon Fuel Standard (LCFS), the SLA-Trona scenario generates an average of $1.375 million in quarterly credit revenue, translating to an additional $0.48 per gallon gasoline equivalent (GGE) of fuel produced at a credit price of $150/MT $CO_2$eq.

## Public Policy-based Revenue Risk

The LCFS revenue, however lucrative, also introduces additional financial variability. The number of credits generated is positively correlated with algae productivity and fuel production, amplifying the seasonal revenue pattern. The highest revenue quarters coincide with high fuel prices and high productivity early in the project's life, as the progressive tightening of the LCFS carbon intensity benchmark reduces credit generation per MJ of biofuel over time. The value of credits generated in a given quarter can range from $500,000 to $6 million depending on production levels and credit price, which has ranged from $110 to $220/MT $CO_{2eq}$ since the program was overhauled in 2016 and has recently declined toward historical lows due to a surplus of banked credits (24).

A potential risk management strategy involves banking LCFS credits during periods of high productivity for sale during low-productivity or low-price periods, functioning as a reserve fund analogous to the cash reserve approach examined by (22). This strategy could smooth seasonal revenue fluctuations and buffer against short-term production disruptions. However, its effectiveness depends on credit price trajectories and regulatory stability, both of which warrant further examination as the LCFS program evolves.

## Limitation & Future Research

Several limitations of this analysis should be acknowledged. First, the growth model was parameterized using a single seasonal dataset (June-September) from small-scale greenhouse ponds (0.18 $m^2$) at the University of Toledo. While the biophysical growth model demonstrates strong correlation with observed data ($R^2 = 0.78$), the extrapolation from these conditions to 5,000 wetted acres of in-ground ORPs over 20-year operating periods introduces uncertainty that cannot be fully quantified with the available data. Model predictions would be strengthened by a full annual cycle of controlled cultivation data from larger outdoor ponds operating under conditions more representative of commercial-scale production.

Second, the dynamic chemistry of the high-alkalinity growth medium is not explicitly modeled. The current analysis assumes high conservation of bicarbonate in the cultivation medium, with losses limited to blowdown and conversion. A time-resolved mass balance of solution carbon, accounting for photosynthetic uptake, night respiration, harvesting, and atmospheric $CO_2$ re-dissolution, is necessary to validate this assumption and to understand whether the alkaline buffer can sustain rapid growth during peak productivity periods without supplementation. Such modeling would also inform operational strategies for medium maintenance and alkalinity replenishment.

Finally, a formal sensitivity analysis examining the influence of key parameters, including Trona price, productivity level, LCFS credit price, discount rate, and biofuel market price, on project NPV and MBSP would strengthen the conclusions drawn here. Our results indicate that productivity and LCFS credit price are likely to be the most influential parameters, but systematic quantification of these sensitivities is warranted and will be the subject of future work. Despite these limitations, the analysis presented here provides the first techno-economic characterization of high pH-high alkalinity algae cultivation using an integrated TEA/LCA framework with stochastic weather and market conditions. The results establish a quantitative foundation for evaluating this production scenario and identify specific areas where further experimental and modeling research can most effectively reduce uncertainty.

# Conclusion

This study presents the first TEA/LCA of commercial scale algal biofuel production using *Chlorella* sp. SLA-04 cultivation in a high pH-high alkalinity medium. The primary results show that the described high pH-high alkalinity production scenario significantly improves the financial competitiveness of algae biofuel. SLA-04 cultivated in a high pH-high alkalinity medium also exhibits lower production variability (CoV) potentially providing more evenly distributed revenue. These findings were enabled by integrating an updated biophysical growth model for SLA-04 into an existing TEA/LCA modeling framework (22) and incorporating bicarbonate and Trona as alternative inorganic carbon sources, allowing for a direct comparison of cost and life-cycle implications across cultivation scenarios. Further experimental characterization of SLA-04 growth at larger scales, dynamic modeling of the alkaline medium chemistry, and formal sensitivity analysis of key economic parameters would strengthen these findings, though the results presented here indicate that high pH-high alkalinity cultivation represents a promising pathway toward commercially viable algal biofuel production.

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## Conflict of Interest

The authors declare no conflict of interest.

## Data and Code Availability

The code and data to replicate the figures and analysis in this manuscript is made available at https://github.com/UNC-Cofires/Biofuels_Spitzer_et_al

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# Supplemental Information

## Updated Pond Temperature Model

Pond temperature is a crucial determinant of algal growth, productivity, and overall plant economics. Earlier versions of the TEA/LCA model estimated pond temperature via an approach adapted from Béchet et al. (2011). The updated TEA/LCA model presented in this study uses a refined model developed in (Greene et al., 2021) which estimates pond temperature at 15-minute intervals considering not only these net heat fluxes but also the heat flux from ground conduction and inflow water, previously assumed to be negligible. In addition, the Greene et al. (2021) model incorporates consideration of the density and specific heat of the SLA-04 algae culture, as opposed to that of the water alone. In the model validation completed in Greene et al. (2021) the model predicted temperature with high fidelity ($R^2$ = 0.95) and represents a considerable improvement over previous model accuracy ($R^2$ = 0.82) (Kleiman et al., 2021). The use of this pond temperature model reduces potential error propagation and provides a more accurate representation of pond thermal conditions, which is important as variability in pond temperature contributes significantly to the variability of algae growth rates (Kleiman et al., 2021; Slegers et al., 2013). The pond temperature model is used to simulate 10,000 (500 simulation runs x 20 years) years of thermal conditions for in-ground ORP's as an input for the biophysical growth model.

## Updated Biophysical Growth Model

An updated biophysical growth model was included in the TEA/LCA model framework presented in this study. A new biophysical growth model described by Greene et al. (2021) is substituted for the previous biophysical growth model developed by Huesemann et al. (2016) that was used in the TEA/LCA developed by Kleiman et al. (2021). The key improvement in the Greene at al. (2021) model is that it is parameterized for six common algae-specific strain characteristics (Table 2), while the earlier model was parameterized for only one, saturation light intensity. These parameters can be determined for any algal species making this modeling framework quite versatile.

*Table S1: Growth Model Parameters for Chlorella sp.* (Bartosh and Banks 2007; Edmundson and Huesemann 2015; Huesemann et al. 2013; Singh and Singh 2015; Wilson and Huner 2000).

| PARAMETERS | VALUE | UNITS (and source) |
|---|---|---|
| SATURATION LIGHT INTENSITY | 230 | $\mu$mol/(m$^2$*s)<br>(Huesemann et al. 2013) |
| OPTICAL DENSITY COEFFICIENT (ODC) | 1.04 | g/(L*OD$_{750}$)<br>(Masojídek et al., 2011) |
| DARK LOSS | 7.5% | (Edmundson & Huesemann, 2015) |
| T_Max | 42 | ˚C<br>(Singh & Singh, 2015) |
| T_MIN | 5 | ˚C<br>(Wilson & Huner, 2000) |
| T OPT | 25 | ˚C<br>(Bartosh & Banks, 2007) |

## Estimating Carbon Demand

In the high pH-high alkalinity configuration, growth is supported by atmospheric mass transfer of $CO_2$, and is estimated by equation 1, where $J_{CO_2}$ is the mass flux of $CO_2$ into the system, E is the enhancement factor for high alkalinity systems (defined in equation 2), $k_L$ is the mass transfer coefficient (estimated with equation 4), $C^*_{CO_2,aq}$ is the equilibrium concentration of $CO_2$ in the aqueous phase based on Henry's law, and $C_{CO_2,bulk}$ is the concentration of $CO_2$ in the boundary layer. (Olander, 1960) derived the formula for the chemical enhancement factor, E, for the mass transfer of $CO_2$ into alkaline solutions based on diffusion coefficients, the aqueous equilibrium concentration of $CO_2$, the equilibrium constant $\mathrm{K}_1$for reaction 3 below and the concentration of hydroxyl ions.

$$J_{CO_2} = E \cdot k_L \cdot (C^*_{CO_2,aq} - C_{CO_2,bulk}) \tag{1}$$

Where,

$$\mathrm{E} = 1 + \frac{D_{OH^-} \cdot D_{HCO_3^-} \cdot K_1 \cdot [OH^-]}{D_{CO_2} \cdot (K_1 \cdot D_{HCO_3^-} \cdot C^*_{CO_2,aq} + D_{OH^-})} \tag{2}$$

$$CO_{2(aq)} + OH^- \rightleftharpoons HCO_3{}^- \tag{3}$$

$$k_{l,2} = k_{l,1} \frac{A_2}{A_1} \times \frac{V_2}{V_1} \times \left(\frac{U_2}{U_1}\right)^{0.65} \left(\frac{H_2}{H_1}\right)^{-1.85} \tag{4}$$

The mass transfer coefficient $\boldsymbol{k}_{\mathbf{L}}$, was estimated using the scaling relationship in equation 4 above and reference data described in Weissman, Goebel, and Benemann (1988). Using equation 1 to model $CO_2$ mass transfer, we can verify that the solution will support algae at the expected growth rates.

At the maximum observed growth rate of 38.5 g $m^{-2}$ $day^{-1}$ (thus at the maximum carbon uptake from the solution, while the average productivity is 12.1 g $m^{-2}$ $day^{-1}$), and at an average carbon percentage of 55%, the mass transfer rate of atmospheric $CO_2$ into the ponds remains above the rate of carbon accumulation of biogenic uptake of $HCO_3^-$ from the solution when a high pH (> 10.1) is maintained (Vadlamani et al., 2019). High velocity mixing – at rates in excess of 0.3 m/s – were unnecessary to sustain this transfer. Also, this estimate only considers the mass transfer at a single point in time and does not account for the night respiration (where algae release $CO_2$ back into the solution and net $CO_2$ dissolution occurs).

Dynamic modelling of solution chemistry to estimate the mass balance of carbon through time and under varying cultivation conditions is outside the scope of this paper. Furthermore, as the maximum growth rate is only achieved during peak hours of peak seasons, $NaHCO_3$ in the cultivation media is assumed to be conserved at a high rate, and losses of $NaHCO_3$ are considered limited to media blowdown and biofuel conversion. In the case of sparging flue gas, sufficient mass transfer of $CO_2$ through the solution media requires an average mixing velocity of 0.2 m/s to prevail annually along with costs associated with $CO_2$ pumping. Whereas in this high pH-high alkalinity approach the operating costs are limited to replacement from blowdown and conversion of the alkaline solutions and a similar average mixing velocity of 0.2 m/s is assumed to prevail annually. In a facility design based on solid inorganic carbon, pump-related head losses are eliminated, and mixing energy requirements decrease by 15% when compared to the scenario requiring high velocity mixing, with changes in mixing energy requirements estimated using the formulas in Lundquist et al. (2010).

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