Combined Algae Processing (CAP): Progress, Challenges, Opportunities, and Future Directions

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National Renewable Energy Laboratory

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List of Acronyms

AD	anaerobic digestion
AFDW	ash-free dry weight
CAP	combined algae processing
CI	carbon intensity
CO_2	carbon dioxide
EXT	lipid-extracted algae biomass
GGE	gasoline gallon equivalent
GHG	greenhouse gas
HAB	harmful algal bloom
HEFA	hydroprocessed esters and fatty acids
HL	high lipid
HP	high protein
HTL	hydrothermal liquefaction
LCA	life cycle analysis
MBPP	maximum biomass purchase price
MBSP	minimum biomass selling price
MFSP	minimum fuel selling price
NIPU	non-isocyanate polyurethane
NREL	National Renewable Energy Laboratory
PU	polyurethane
SAF	synthetic aviation fuel
TEA	techno-economic analysis
WWT	wastewater treatment

Abstract

This white paper summarizes the historical progress and perspectives on future opportunities for combined algae processing (CAP), a conversion approach centered around fractionating microalgae biomass and producing a slate of fuels and products from its compositional constituents. We discuss the critical challenges associated with the commercialization of algal biofuels and demonstrate how the CAP approach is uniquely suited to overcome these barriers. The versatility of applying CAP to various sources of algae is highlighted, along with conversion to a range of fuels and products.

Introduction

Microalgae have long been recognized as a promising feedstock for producing fuels and products, offering advantages such as rapid biomass growth, high carbon dioxide (CO_2) uptake potential, and the ability to grow on non-arable land and saline water [1–4]. Additionally, the unique compositional makeup of algae enables very high oil and fuel yields alongside value-added products. Most algae species exhibit a flexible storage carbon metabolism and compositional changes over a growth cycle, reflecting a transition from high-protein (HP) biomass under more productive nutrient-replete conditions, to high-carbohydrate, and finally to high-lipid (HL) as dense energy stores accumulate—making HL algae especially promising for lipid-based fuel production. Altogether, the attributes of microalgae make it a scalable and flexible alternative to traditional oilseed crops, which are a leading option for producing bio-based fuels but face increasing challenges related to limited supply and price volatility. The agronomic advantages of microalgae are summarized in Table 1 and compared with soybeans—the most common oilseed crop used for lipid-based fuel production in the United States—and pennycress—an oilseed cover crop that can be grown within existing crop rotations [5].

To capitalize on the strengths of microalgae, teams at the National Renewable Energy Laboratory (NREL) have pioneered research on a nondestructive fractionation approach, termed "combined algae processing" (CAP) [6–8]. The CAP approach targets the valuable (and highly variable) compositional profile of algal biomass, using biochemical processing concepts to isolate and sequentially upgrade algal lipids, carbohydrates, and proteins to a slate of fuels and/or products. Notably, this also includes upgrading algal lipids to synthetic aviation fuel (SAF) via the hydroprocessed esters and fatty acids (HEFA) pathway, a commercially established technology already being deployed for ASTM-certified SAF production from other vegetable/waste oil feedstocks (albeit under severely feedstock-constrained limitations, a bottleneck that algal lipids could greatly alleviate in the future) [9].

Table 1. Annual Production Metrics for Microalgae Compared to Terrestrial Oilseed Crops Soybeans and Pennycress

All metrics are reported on the basis of one year (microalgae) or one growing season (soybean and pennycress). References for each metric are provided in brackets; values without references are calculated.

Metric	Unit	Microalgae		Soybean		Pennycress	
Biomass yield	dry tons/acre	47.5–56.6	[5,10]	1.0–1.4	[11]	0.4–1.1	[12]
Oil yield	gal oil/acre	1,012–7,143		50–79		40–111	
	gal oil/dry ton	21–126	[13] [a]	48–59	[14] [a]	101	[5] [a]
CO_2 uptake	tons/acre	92–118		1.6–2.1		0.6–1.7	
	tons/dry ton	1.9–2.3	[10] [b]	1.6	[15]	1.6	[15] [c]
Nitrogen requirement	lb N/acre	7,004–8,976		0–75	[16] [e]	0–50	[17]
	lb N/dry ton	147–159	[10] [d]	0–72		0–125	
Phosphate requirement	lb P_2O_5/acre	4,184–5,329		0–100	[16]	0–20	[17]
	lb P_2O_5/dry ton	88–94	[10] [d]	0–96		0–50	
Potassium requirement	lb K_2O/acre	0–113		0–120	[16]	0–20	[17]
	lb K_2O/dry ton	0–2	[18] [f]	0–115		0–50	

Metric	Unit	Microalgae		Soybean		Pennycress	
Fresh water	gal/acre × 10^3	0		407–679	[19]	86–237	
	gal/dry ton × 10^3	0	[10] [d]	301–650		216	[20]
Saline water	gal/acre × 10^3	1,303–3,526		0		0	
	gal/dry ton × 10^3	27–62	[10] [d]	0		0	

[a] Calculated using an oil density of 0.9 g/L and lipid content of 8%–47% for microalgae (high-protein and high-lipid biomass modeled in Wiatrowski et al. [13]), 18%–22% for soybeans [14], and 38% for pennycress [5].
[b] Calculated from carbon content for high-protein and high-lipid biomass modeled in Wiatrowski et al. [13].
[c] Pennycress carbon content assumed equivalent to soybean.
[d] Calculated from minimum/maximum values of the three representative cases for low, medium, and high biomass costs presented in [10].
[e] Supplemental nitrogen may be used in soybean production in some cases, but soybeans do not require nitrogen addition due to their ability to perform nitrogen fixation.
[f] Potassium requirements for algae cultivation are typically low and may be met by the potassium content of the saline groundwater used (not explicitly included in production models).

However, a key challenge remains the high cost of producing algal biomass—estimated at roughly $500/ton or more, even for future target projections—for a dedicated algae farming approach analogous to the farming of conventional crops. This cost is generally higher than the market price of soybeans ($340/ton [5], ranging from $276 to $550/ton from 2020 to 2024 [21]), exceeds the range of projected costs for pennycress ($100–$500/ton), and is at least an order of magnitude greater than non-oilseed terrestrial biomass feedstocks such as woody biomass or corn stover (typically on the order of $60–$80/ton for similar future projections), though in the latter feedstocks much of their carbon is stored in recalcitrant compounds more difficult to access such as lignin [5]. Biomass costs could potentially be offset by fuel alone as the sole product in scenarios demonstrating the highest ranges of fuel yields that could be practically achievable (at least 125 gasoline gallon equivalents [GGE] per ton of ash-free dry weight [AFDW] biomass) [8,13]. These values are within reasonable limits for algal biomass and some oilseed crops (albeit at much lower yields on a per-acre basis for oilseed crops), but well exceed achievable fuel yields from other terrestrial crops such as woody biomass and corn stover, which are typically on the order of 40–80 GGE/ton [22,23]. Still, barring these scenarios with exceptionally high fuel yields, the cost of algal biomass necessitates the inclusion of other revenue sources beyond the sale of fuels (or otherwise sourcing biomass from lower-cost options, discussed later). Such revenue streams could stem from inclusion of higher-value coproducts that can be made from algal biomass constituents, as well as supplemental revenue from sale into markets incentivized by carbon reduction policies.

This point is highlighted in Figure 1, which considers the economic feasibility (represented by the minimum fuel selling price [MFSP]) and fuel carbon intensity (CI) of a conversion approach tailored for high-lipid (HL) algae biomass, consistent with the HL scenario presented in Wiatrowski et al. [13]. This approach extracts algal lipids and isolates the polyunsaturated fatty acid fraction of the lipids for conversion to a high-value non-isocyanate polyurethane (NIPU) coproduct (using intermediates in its synthesis with reduced toxicity and the potential for additional emissions reductions compared to conventional polyurethane [PU]), with the remainder of the lipids converted to fuels. MFSP and CI are plotted across a range of biomass compositions and cultivation productivity rates, the latter representing the strongest single driver on algal biomass production costs from upstream algae farming. Lipid and protein content in the biomass are varied in concert within their typical ranges (5%–45% for lipids while simultaneously reducing protein from 50% to 10%, reflecting their inverse relationship), while productivity is varied over a range of 10–25 g/m^2/day (within the range of seasonal productivities demonstrated during long term cultivation trials at an algae testbed [24]) to demonstrate the effect brought by these parameters on algae biorefining. Even including revenue from the coproduct, achieving a satisfactory lipid content (and an accordingly high fuel yield) is essential, with values greater than 30%–35% (76–89 GGE/ton AFDW) required to reach MFSPs below $5/GGE and CI reductions exceeding 50% compared to petroleum fuels. However, achieving these thresholds also requires sufficiently high biomass and lipid productivities and resultant reductions in biomass production costs, recognizing there is often a penalty in achievable productivity to support HL biomass relative to HP biomass, a challenge that has been the focus of substantial strain engineering efforts to overcome.

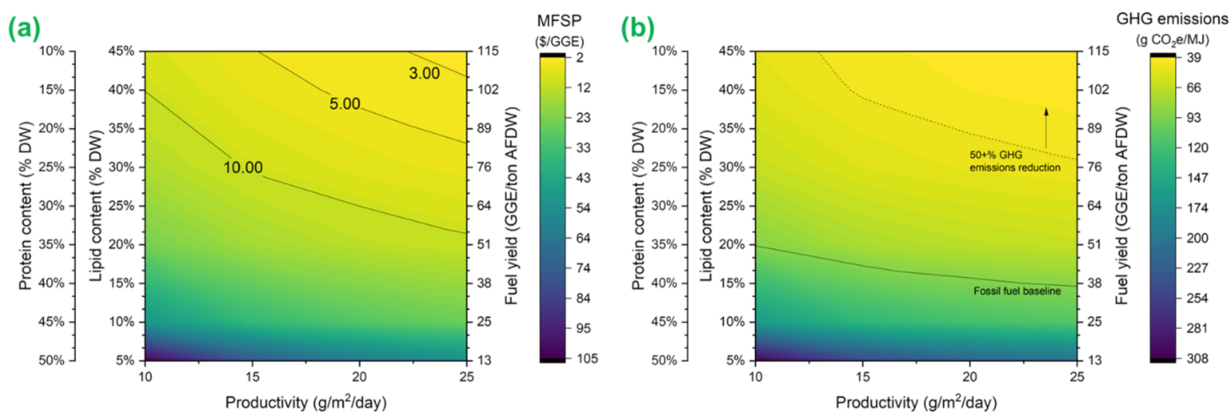


Figure 1. Variation of (a) MFSP and (b) CI of algae-derived fuels as a function of biomass productivity and biomass composition. The biorefining approach (consistent with a conversion scenario for HL algae biomass modeled in Wiatrowski et al. [13]) extracts and splits lipids for the production of hydrocarbon fuels and NIPU and sends the residual biomass to anaerobic digestion. Fuel CIs are calculated using the mass allocation method.

Fortunately, the CAP approach is optimally suited to support a multi-fuel/multi-product biorefinery concept necessitated by the economic challenges noted above. CAP processing leverages a low-pH aqueous slurry pretreatment at moderate temperatures, yielding an aqueous solution of hydrolyzed (and primarily monomeric) saccharides and an insoluble fraction rich in lipids and protein, primed for subsequent organic solvent extraction of the lipids, leaving a protein-enriched residue. The solubilized carbohydrate and extractable lipid fractions are entirely compatible with well-known conversion pathways such as fermentation and vegetable oil HEFA processing respectively. In contrast to higher-severity thermochemical conversion approaches that typically convert the whole biomass feedstock to organic, aqueous, solid, and gaseous phases indiscriminately (largely destroying the compositional constituents in the process), CAP allows for a more selective and non-destructive fractionation of unique algal biomass components for subsequent valorization to fuels or products. This is shown in a simplified form in Figure 2, depicting a generic pretreatment (typically dilute acid pretreatment, though other methods such as alkali or thermal/flash hydrolysis pretreatment have also been evaluated with some efficacy [25]) followed by extraction of lipids (which may be hydrotreated to fuels or catalytically converted to high-value products such as polyols or PU). Fermentation or other upgrading options may be used to convert sugars to fuel or chemical/polymer precursors, and proteins may be converted to products, used in food/feed applications, or converted to biogas via anaerobic digestion (AD) for energy recovery and nutrient/CO_2 recycling. Other minor components may likewise be isolated and upgraded, such as surfactants from algal sterols [26].

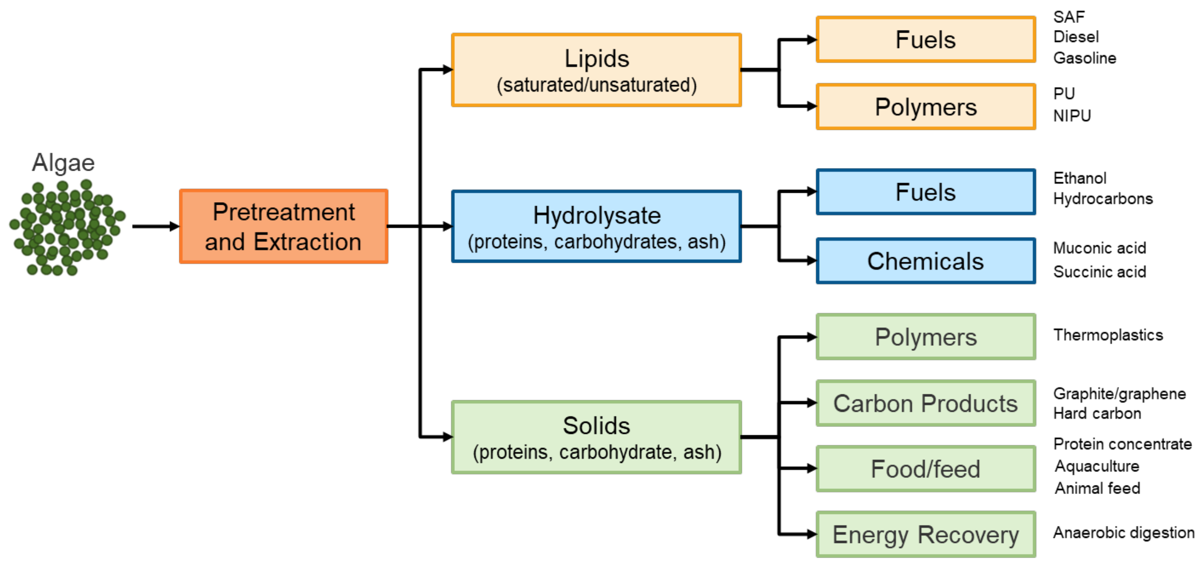


Figure 2. Flow diagram showing the CAP fractionation approach and the potential coproducts that can be produced from each fraction

Over the past decade, NREL has evaluated more than 20 different conversion configurations for producing fuels and products from the various microalgae fractions, alongside six pretreatment methods and two lipid extraction techniques. These configurations have been investigated through experimental trials (coordinated under NREL's Combined Algal Processing for the Synthesis of Liquid Oleofuels and Products [CAPSLOC] project) and techno-economic analysis (TEA) and life cycle analysis (LCA) modeling (coordinated under NREL's Algae System TEA project). Figure 3 provides a snapshot of MFSP following the evolution of CAP through iterative TEA modeling reflecting key stages of fuel/coproduct development [7]. The evolution illustrates historical approaches focused only on lipid extraction (upon reestablishment of a multi-year NREL algae program around 2011) [1], followed by the introduction of the CAP approach in 2014 with parallel upgrading of algal sugars to ethanol [8], by itself enabling an MFSP reduction of roughly $3/GGE due to higher fuel yields enabled by coproduction of ethanol. Later, ethanol was replaced with higher-value product options from sugars such as succinic acid (investigated in NREL's 2015 algae state-of-technology update), highlighting the potential for an additional $2/GGE MFSP reduction to nearly $3/GGE, potentially supplemented by other coproduct options such as surfactants [27].

Following a strategic pivot away from succinic acid around 2017, fungible/hydrocarbon fuels that can be produced fermentatively from the carbohydrate fraction such as 2,3-butanediol (BDO) and carboxylic acids were prioritized instead. This enabled high hydrocarbon fuel yields above 90 GGE/ton AFDW (focused primarily at the time on diesel and gasoline) and associated carbon retention to fuels (over 40% of biomass carbon), albeit at somewhat higher costs than the algal sugar-to-ethanol route, i.e. comparing the second and fourth bars in Figure 3 [28]. Subsequently, beginning in 2020, the focus pivoted again toward maintaining high fuel yields while incorporating high-value and high-market volume coproducts, primarily enabled by diverting a fraction of lipids to PU, highlighting a path to less than $2.5/GGE MFSPs, a more favorable outcome than any other configuration as a means to ultimately achieve economic viability [29,30]. These example cases were all based on a historical target algal biomass composition prioritizing carbohydrate enrichment with moderate levels of lipids and protein (reflecting the biomass composition of a high-carbohydrate *Scenedesmus* strain), to take advantage of well-understood sugar fermentation pathways. However, more recently NREL teams have further shifted focus to consider biomass with either high lipid or high protein content reflecting the more unique compositional attributes of algae, given more options for lower-cost carbohydrates from conventional terrestrial biomass. One promising approach reflected in a 2025 report [13] focused on HL biomass conversion and incorporated NREL's novel NIPU technology in place of conventional PU, maintaining a sufficiently low MFSP while significantly increasing fuel yields under reduced processing complexity as compared with the 2020 case (121 GGE/ton AFDW versus 72 GGE/ton AFDW for the 2020 scenario). NIPU technologies, as well as alternative approaches using conventional PU routes in combination with bio-based polyols and isocyanates [31], represent an emerging set of technologies with the potential to accelerate the proliferation of algal biofuels.

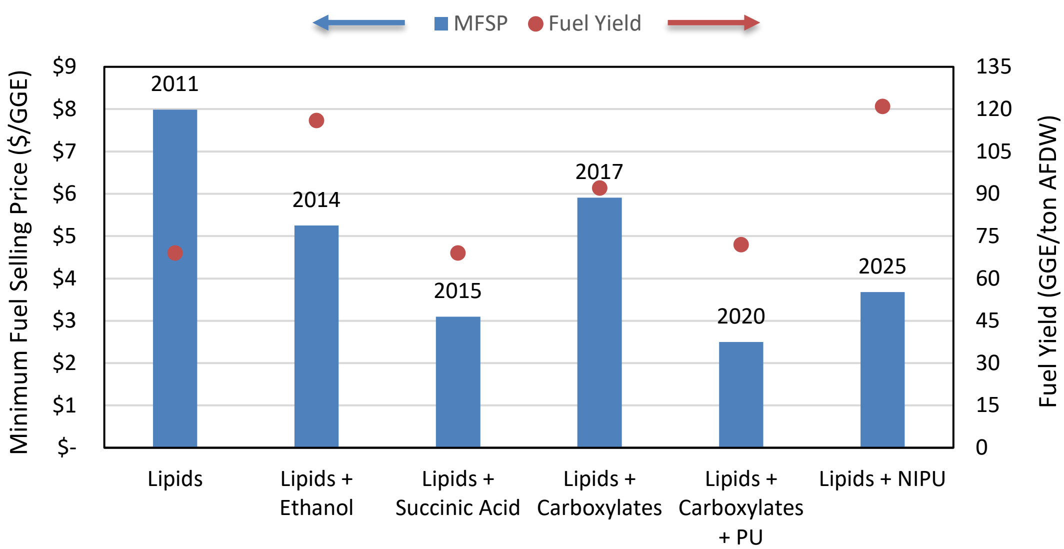


Figure 3. Evolution of CAP configurations investigated through R&D and TEA modeling.

MFSP (blue bars) is shown on the left axis, and fuel yield (red markers) is shown on the right axis. Labels indicate the approximate year in which each analysis was performed, in line with evolving experimental focus on these CAP concepts over time. All scenarios reflect a high-carbohydrate biomass with moderate lipid levels except for the 2025 scenario, which reflects an HL biomass (47% lipids, consistent with that modeled in Wiatrowski et al. [13]).

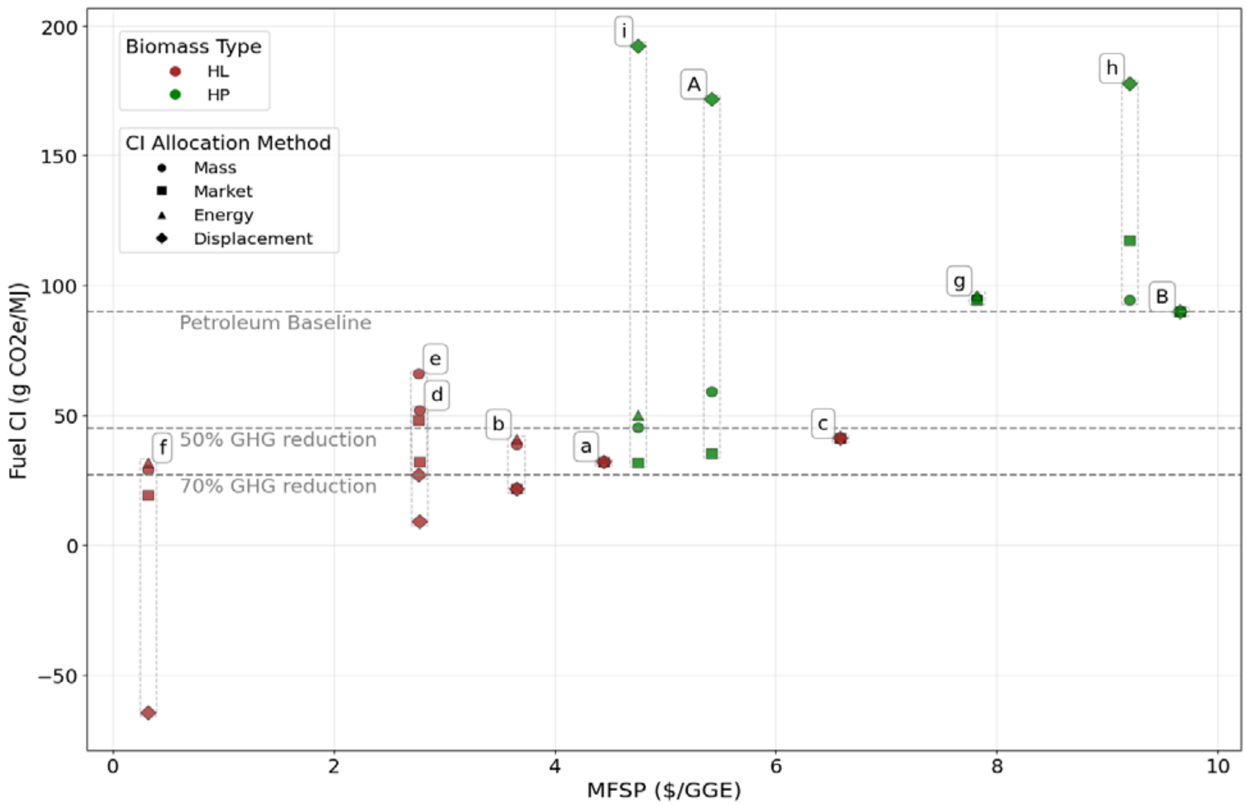
Economics and Carbon Intensity

TEA/LCA Trade-Offs for Conversion of Farmed Algal Biomass

To understand how economics and carbon intensity are each influenced by biomass composition and CAP conversion approach, it is helpful to refer to the variety of published TEA and LCA results for CAP processes. Figure 4 shows the MFSP (adjusted to 2020 dollars for all scenarios) and fuel CI of various published CAP approaches. For further context, alternative cases utilizing hydrothermal liquefaction (HTL, a higher-severity thermochemical processing approach for whole biomass conversion to fuels) are also included for comparison. In cases including coproducts, fuel CIs can be calculated using various allocation methods, including displacement, mass-based allocation, market-based allocation, and energy-based allocation, and results may vary significantly depending on the method applied. High-value (>$500/ton) coproducts included in pertinent cases are shown in the table below the plot.

The reliance on coproducts and the stark contrast between HP and HL biomass outlined above is evident in Figure 4, with most HP scenarios (shown in green) reflecting challenging economics and generally failing to exceed a 50% greenhouse gas (GHG) reduction threshold compared to petroleum fuels. Particularly, for HP biomass conversion scenarios without high-value coproducts, the fuel CIs were calculated to be of the same magnitude as petroleum fuels and MFSPs were greater than $9/GGE. The most promising HP scenario (labeled "j") is associated with an approach that includes two high-value products (PU foams and thermoplastic co-feed), a challenging level of complexity for deployment in the near-term.

In contrast, several HL scenarios show the potential to exceed 50% GHG reductions and achieve much more favorable economics if biomass productivity rates can be preserved alongside a compositional shift. The most favorable cases all include some form of a PU coproduct, though several HL scenarios without a coproduct also show the potential to exceed 50% GHG reductions while approaching reasonable costs (prior to considering factors such as potential policy credits, not otherwise included in this summary). Despite some variations in the detailed assumptions behind each analysis (such as lipid content, algae farm size, and specific coproduct considerations), these compiled results indicate that HP algal biomass processes often struggle to meet economic targets and favorable carbon intensities due to inherently low potential for fuel production, while compositions with elevated levels of lipids offer a clear advantage in both metrics, across varying conversion strategies. Notably, HTL conversion similarly suffers from challenging costs and GHG metrics for HP algae, either with or without inclusion of high-purity protein coproducts, based on a recently published algae harmonization report [10] (included for reference as points "A" and "B" on the plot, in this case focused on higher-value whey protein in point "A," albeit under more limited market volume capacities for such protein products).



Label	Biomass	Scenario	Coproducts	Fuel Yield (GGE/ton)	Reference
a	HL	2014 design report – high-lipid *Scenedesmus*	None	141	[8]
b	HL	Technology case study – HL	NIPU	121	[13]
c	HL	Technology case study – HL (fuel only)	None	140	[13]
d	HL	2030 state-of-technology target – carboxylic acid pathway	PU	72	[29]
e	HL	2030 state-of-technology target – BDO pathway	PU	73	[29]
f	HL	2023 state-of-technology; industry case study – carboxylic acid pathway	PU	81	[24]
g	HP	Technology case study – HP	Thermoplastic	37	[13]
h	HP	CAP: fuels (lipids and mixed alcohols) + feed	Feed	54	Unpublished
i	HP	2022 HP manuscript – mixed alcohols plus upgrading	Thermoplastic + PU	43	[32]
A	HP	HTL – 2022 harmonization (fuel + whey protein concentrate)	Whey protein concentrate	52	[10]
B	HP	HTL – 2022 harmonization (fuel only)	None	97	[10]

Figure 4. MFSP and fuel CI of various CAP conversion approaches assessed previously.

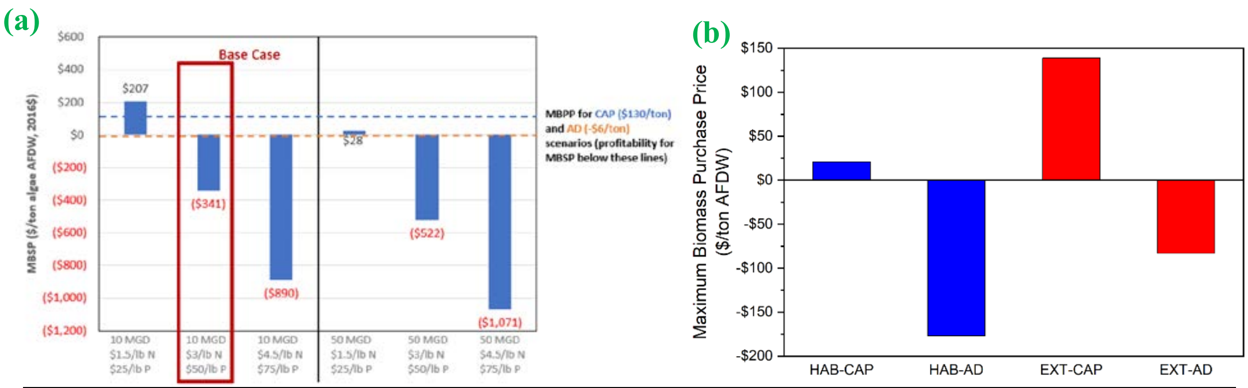
Biomass compositions reflecting an elevated level of lipids are shown in red, while compositions with lower lipid levels and higher protein levels are shown in green. Additional details for each scenario are included in the table below the plot. All scenarios reflect variations of a CAP configuration with the exception of A and B, which show results for HTL of HP biomass. Fuel CIs are calculated using multiple approaches, including mass-based allocation, market-based allocation, energy-based allocation, and displacement. MFSPs for all scenarios are adjusted to 2020 dollars. Fuel CIs for scenarios without a published LCA are estimated using data from the 2023 Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model [33].

Opportunities for Low-Cost Algae

As an alternative to high-cost biomass produced from dedicated algae farming approaches and resultant challenges highlighted above, conversion of algae could be more practical when sourced from lower-cost biomass, which may be viewed as either a waste or a byproduct of higher-value revenue streams. Such "waste" algae resources may be produced in wastewater treatment (WWT) facilities, where the primary value comes from mitigation of nitrogen and phosphorus in waste effluent streams to mandated levels, or collected from naturally occurring harmful algal blooms (HABs). Additionally, "waste" byproduct algal biomass could be procured from current commercial operations focused on extracting nutraceutical products such as omega-3 fatty acids (lipid-extracted algae biomass, referred to as "EXT"). In the latter case, while the algae are originally cultivated in dedicated farms, it is for the sole purpose of producing such highly valuable components where most or all revenue comes from, leaving minimal economic dependence on the residual lipid-extracted biomass fraction. In such scenarios, algal biomass could potentially be sourced at near-zero cost or even negative costs (when facilities avoid a "tipping fee"), and thus greatly expanding the opportunity space for CAP conversion applications—though also recognizing a trade-off in usually lower quality biomass (lower lipids, higher inorganics and moderate to high protein content) and lower national-scale biomass potential for such waste algae resources (e.g., 28 million tons/year potentially produced from WWT [34]) compared to conventional farming (152 million tons/year as highlighted in the 2022 harmonization report [10]).

To highlight this point, in 2022 NREL published a report specifically investigating TEA implications for sourcing and conversion of this HP algal biomass as may be procured from all three waste industry applications [34]. The report was organized into WWT (as the most readily implementable option) and HAB/EXT resources (as smaller-scale or longer-term resource options). In the case of WWT, the analysis compared the cost of producing algal biomass (minimum biomass selling price [MBSP] when viewing water treatment nitrogen/phosphorus mitigation as a coproduct revenue stream) against the maximum allowable biomass purchase price (MBPP) that a CAP biorefinery would be able to pay in order to make fuels/products economically. In the case of HAB/EXT biomass, a similar MBPP metric was calculated to highlight a path to economic viability for similar CAP configurations under low-cost algal biomass feedstock prices, which in the HAB case could in turn be used to identify water cleanup credits that would be required to collect the biomass at an equivalent cost.

Key results for this study are summarized in Figure 5. For WWT algae, Figure 5(a) highlights the MBPP (dashed lines) required to achieve economic viability for either AD processing of the biomass or a simple CAP pathway entailing extraction of lipids for fuels, fermentation of carbohydrates to ethanol, and valorization of residual solids for coproduction of bioplastics (the latter approach is currently in practice by at least one commercial entity, who has demonstrated effective incorporation of waste/low-quality algal biomass into bioplastics). As long as the biomass can be produced/sourced for an MBSP cost less than this MBPP threshold, the overall system will be economically viable, even under small-community-scale biomass feed rates. Indeed, in five of the six scenarios considered, WWT algal biomass could be produced at an MBSP comparable to or significantly lower than the MBPP, only failing to achieve profitability at a smaller 10-million-gallon/day WWT scale coupled with conservatively low nitrogen/phosphorus mitigation credits, with most other cases highlighting the potential for negative MBSPs (where the revenue stream from water treatment as a service outweighs the operation and capital costs of algal biomass production, and thus would easily support a profitable conversion system to fuels/coproducts). For HAB/EXT algae, Figure 5(b) highlights similar MBPP ranges up to $150/ton that a small-scale CAP or AD biorefinery would be willing to pay for incoming algal biomass feedstock in order to achieve at least 10% or greater internal rate of return profitability for conversion to fuels/products. This again favors CAP at a higher MBPP, indicating a potentially more viable route than AD for either biomass source (utilizing the same CAP approach as for WWT but now excluding lipid extraction). Particularly in the CAP case, there is a good likelihood that either biomass resource could be procured at a cost less than its respective MBPP (provided sufficient water cleanup credits in the case of HAB biomass collection).



Scenario	Products
WWT–CAP	Ethanol, lipids (for fuels), thermoplastic co-feed, nutrient-rich crop water
HAB–CAP and EXT–CAP	Ethanol, thermoplastic co-feed, nutrient-rich crop water
All AD scenarios	Renewable natural gas, AD digestate fertilizer, nutrient-rich crop water

Figure 5. (a) Minimum Biomass Purchase Price (MBPP) that a CAP or AD biorefinery would be willing to pay (dashed lines) for waste algal biomass produced from municipal WWT while maintaining profitability, compared to much lower biomass production costs (MBSP, shown as bars)—in many cases becoming negative—for cultivating WWT algal biomass supported by nitrogen/phosphorus mitigation credits. Results are shown for varying wastewater scales and nutrient treatment credits. (b) MBPP for a CAP or AD biorefinery to produce fuels/products at similarly small scales as may be sourced from HAB or EXT resources. MBSPs for these scenarios are less straightforward to calculate but are likely to again be less than the MBPPs, at least for CAP conversion (contingent on water cleanup credits in the HAB case).

Scalability and Market Potential

While still in the nascent stages of commercialization, the scaling and supply chain impact potential for microalgae conversion and processing is substantial and provides a path to alleviate known HEFA feedstock supply chain bottlenecks for biofuels production. A recent harmonization effort by a collaboration of national laboratories [5,10] set out to quantify this potential by identifying all sites in the continental United States that met the criteria for an algae farm (including land, water, and CO_2 availability constraints) and assessing the cost and sustainability implications of each site. The analysis indicated that up to 3.9 million acres of land across 980 sites could yield 151 million tons of AFDW biomass per year, highlighting a substantial opportunity for producing large volumes of fuels and products. Through the leading CAP approaches outlined recently [13], this biomass could result in the production of 14.1 billion GGE of fuel per year (8.3 billion gallons of SAF) from HL biomass, or alternatively produce 5.4 billion GGE of fuel (3.1 billion gallons of SAF) from HP biomass with lower levels of lipids.

These results highlight the potential for microalgae to make a substantial contribution to domestic energy production and support expansion of the bioenergy supply chain, leveraging the most technologically mature ASTM-approved pathway for producing SAF via HEFA processing already being deployed today on other feedstocks. The first 100 facilities could provide 0.5-1.4 billion GGE per year (from HP and HL biomass, respectively) while also significantly expanding the production of bio-based coproducts, producing 1.7 million tons of NIPU foam (HL biomass) or 10.0 million tons of thermoplastic co-feed (HP biomass). Leading approaches focus specifically on rigid NIPU foam and ethylene vinyl acetate as target coproducts; however, as replication occurs, cost reductions driven by learning curves and ongoing R&D could accelerate commercialization of alternative co-product opportunities. This would allow for broader product portfolios (e.g., producing other PU/NIPU products or expanding into other thermoplastics from HP solids), opening up additional market opportunities and enabling further production of fuels and products from microalgae.

Despite significant potential, algal biofuels remain in a precommercial state, primarily hindered by the lack of large-scale deployment and demonstration successes. Algae-related R&D has been advancing for decades, with various groups demonstrating important technological progress toward producing biomass, fuels, and fuel precursors. However, most commercial successes to date have centered on producing high-value products such as dietary supplements, pigments, cosmetics, and pharmaceuticals. These markets provide the revenue potential needed to offset biomass costs, but their relatively small size has limited algae farm development to facilities generally smaller than 200 acres. Other efforts have focused on applying algal systems for wastewater treatment, generating biomass as a secondary product that can serve as a feedstock for additional ventures such as polymer production. In almost all cases, a common thread is a requirement to either produce at least one high-value product to offset high feedstock costs or to convert low-cost, lower-quality byproduct biomass into fuels and other energy products. The versatility of algae as a bio-based feedstock makes it well suited for both strategies, and the CAP approach provides a robust framework to fully harness this potential.

Conclusion

Microalgae offer a promising solution for producing a range of bio-derived fuels and products, and the inherent flexibility of the CAP approach makes it uniquely suited to capitalize on this potential. While microalgae composition may vary significantly depending on cultivation system, biomass strain, and environmental conditions, the CAP conversion approach can be tailored to the constituents available in the biomass, optionally employing lipid extraction, fermentation, and various solid residue handling approaches. This tailored approach is designed to meet the challenging cost of the biomass by maximizing the value extracted. As advancements in algae cultivation continue to push limitations on biomass productivity, composition, cultivation robustness, and operability, continued research on variations of the CAP approach is essential to establish and advance key technologies for fractionating and upgrading the biomass.

The breadth of research conducted to advance the CAP pathway feasibility lays a strong foundation for supporting the commercialization of algae conversion. Key technologies researched at NREL support this advancement; scale-up and optimization of core unit operations such as pretreatment, extraction, and hydrotreating are essential for making algal biofuels viable. For biomass with exceptionally high lipid content and productivity, these operations may be sufficient. However, in most cases, economic feasibility cannot be demonstrated with fuels alone and advancing breakthrough research on coproducts such as PU (including conventional and non-isocyanate), carbon products, and other polymers can offer the supplemental revenue needed to accommodate high biomass costs. Additionally, earlier-stage discovery research is still needed, especially for identifying feasible pathways for converting low-cost HP algae. At each stage of research, TEA and LCA can help identify the most promising approaches and configurations and establish target values for essential performance metrics that must be met to support commercialization.

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