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Hydrothermal liquefaction of wastewater-grown algae to produce synthetic aviation fuel: A combined experimental study and techno-economic assessment☆

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ABSTRACT

Large-scale algae farms may someday become a consistent source of biomass feedstock for biofuels. Near-term supplies of algal biomass are available at certain water resource recovery facilities as algae cultivation is used as a method for nutrient recovery from specific effluent streams. Algae grown as a service shifts the value to the service rather than its sole use as a feedstock, which could enable the provision of algal biomass at low to no cost to biofuel producers. Hydrothermal liquefaction (HTL) can readily upgrade wet feedstock slurries, such as algae, to produce a carbon-enriched biocrude. The HTL biocrude can be hydrotreated and distilled, producing a variety of distillate fuels, including synthetic aviation fuel (SAF). We present a pathway, showing the experimental production of SAF from wastewater-grown algae via HTL, along with a techno-economic assessment to identify opportunities for process improvements. Critical quality attributes of the SAF, such as density, viscosity, surface tension, and freeze point, were estimated within the expected fuel experience ranges when compared against petroleum jet fuel. The average minimum fuel selling price of fuels from wastewater-grown algae for breakeven economics was $9.04 per gasoline gallon equivalent (GGE). The sale of co-products such as struvite fertilizers and cement additives can add revenue to reduce the net cost. Ultimately, the selling price is influenced by the scale of the HTL processing facility. Adjusting estimations in the process scale, algae yield, and capital cost estimation can lower the price to $6.51/GGE or raise it to $13.07/GGE.

Introduction

The United States processes approximately 34 billion gallons (129 million cubic meters) of wastewater per day, producing over 15 million US tons (14 billion kg) of solids per year. Of the solids produced, half are anaerobically digested to further reduce the volume of solids [1]. Post digestion, additional treatment is needed to minimize solids and recover the remaining nutrients in the liquid digestate. Algae biofilm reactors are a recently developed technology that can reduce chemical and energy requirements for nutrient recovery from liquid digestate and other wastewater streams. Some water resource recovery facilities (WRRFs) have recently implemented algae biofilm reactors in their treatment facilities to aid in nutrient removal [2,3]. Biofilm reactors operate by slowly moving a growth substratum (such as nylon or polyester fabric) in and out of wastewater, which provides the biofilm-forming algae with alternating access to water and dissolved nutrients (nitrogen and phosphorus) and exposure to sunlight and atmospheric carbon dioxide for growth [4,5]. The devices are intended to provide nutrient recovery at reduced operating costs for WRRFs. However, the reactors are also a source of algae biomass, which can be pelletized and sold directly as

Abbreviations: DCN, derived cetane number; GCxGC-FID, two-dimensional gas-chromatography with a flame ionization detector; GGE, gasoline gallon equivalent; HHV, higher heating value; HTL, hydrothermal liquefaction; ICP-OES, inductively coupled plasma optical emission spectroscopy; IRR, internal rate of return; LHV, lower heating value; MFSP, minimum fuel selling price; SAF, synthetic aviation fuel; TEA, techno-economic analysis; WRRF, water resource recovery facility.

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fertilizer or treated to make fuels and other products [6,7].

Currently, producing slow-release fertilizer in the form of pelletized algae biomass is a commercially implemented method for using biomass produced from algae biofilm reactors [3]. Using the produced algal biomass as a fertilizer is functionally similar to the land application of digested biosolids, but the process discards 12–26 MJ/kg of energy stored in wastewater-grown algae biomass [8–12]. Instead, fertilizer production from algae biomass could be coupled with energy recovery via hydrothermal liquefaction (HTL). HTL is a conversion process that uses high pressure (≥200 bar) and moderate temperature (250–350 °C) to emulate the natural processes in crude oil formation [13,14], and can consistently recover over 50 % of the energy in algae biomass [15,16]. During HTL, wet biomass is transformed into biocrude, gas, water-soluble compounds, and a solid residue. The HTL solids can retain over 90 wt% of the phosphorus and ash contained in the input biomass [17,18]. The phosphorus in the solid residue can be recovered by extraction with acid and then precipitated as struvite ($MgNH_4PO_4 \cdot 6H_2O$) [19], which can be sold as fertilizer. The inorganic elements from HTL solids have also been proposed for use as cement additives [20]. HTL is particularly suited for energy and mineral recovery from wastewater-grown algae because it can simultaneously upgrade algae and other wastewater solids, which enables large processing scales and comparatively low biofuel costs [16]. The biocrude products generated during HTL are similar to petroleum crude oil and can be upgraded to distillate fuels such as gasoline, synthetic aviation fuel (SAF), and diesel [13,14].

In this study, the critical fuel properties of SAF produced from wastewater-grown algae via HTL are examined for the first time. Domestic production of aviation fuel is important for reducing demand for imported fossil fuels. Demand for aviation fuel represents about 8 % of all petroleum fuel consumption in the United States [21] and could reach much higher shares in future scenarios with increased demand for air travel. SAF can be produced using different technologies, such as lipid extraction of biomass to produce hydroprocessed esters and fatty acids or gasification of biomass coupled with Fischer-Tropsch processing to produce alkanes [22]. The aforementioned processes use various feedstocks, including used cooking oils, food waste, or whole biomass. Consequently, the properties of SAF can vary significantly between SAF production schemes. Demonstrating the safety and reliability of SAF produced by a new process requires fuel candidates to undergo a series of qualification tests requiring gallons of fuel [23]. Gallon-scale testing of new SAF products can be prohibitively expensive for early-stage fuel production research; thus, small-scale preliminary analysis methods are used to predict fuel characteristics prior to large-scale production [24]. A low-volume approach with fast turnaround for feedback enables researchers and fuel producers to adjust fuel production parameters to meet the desired properties. The critical properties of SAF assessed in these tests include the fuel's derived cetane number (DCN), flash point, energy content, density, kinematic viscosity, and distillation characteristics and are described in detail elsewhere [25].

Previously, we demonstrated that the critical fuel properties of SAF produced from pond-cultivated *Picochlorum celeri* fall within the expected experience ranges for conventional jet fuel [26]. Subsequent analyses have quantified the aliphatic and aromatic compounds in hydroprocessed fuels produced via HTL of *Chlorella* [27], *Spirulina* [28], and wastewater-grown algae [29]. The compositions and properties of biocrude and distillate fuels produced via HTL are dependent on the composition of the feedstock [27] and on the processing conditions used for conversion [30] and upgrading [28] into finished products. Similarly, the economic viability of producing SAF and other fuels from algae depends on the scale of production, the feedstock-specific biocrude yield, and other details of the conversion scenario [31].

Here, we assess the critical fuel properties of SAF produced from a wastewater-grown algae-bacteria biofilm consortium, which represents a currently available low-cost algae feedstock. Prior to this analysis, the critical fuel properties and cost of SAF produced from this feedstock were not known. We present an experimental demonstration showing the conversion of this feedstock into SAF. The demonstration is coupled with process and economic modeling to benchmark the potential costs for a new production scenario for SAF. The scenario modeled in this study is presented in Fig. 1 and includes biomass processing via HTL, biocrude upgrading into finished fuels, nitrogen and phosphorus recovery from the solid and aqueous HTL product streams, and the production of supplementary cementitious materials from the material residues from fuel and fertilizer production. To the best of our knowledge, this is the first report on the critical properties of SAF produced from wastewater-grown algae via HTL and the first report on the cost of distillate fuels produced from wastewater-grown algae via HTL with simultaneous production of both struvite and cement additives as co-products.

2. Materials and methods

2.1. Hydrothermal liquefaction

The wastewater-grown microalgae, simply referred to as algae, used in this study were produced using a fixed-film bioreactor at a municipal wastewater treatment facility in Iowa City, IA, USA. Liquid digestate from an anaerobic digestion unit was used as the sole cultivation media for the algae. The cultivation system and its operation have been described previously [5]. Previous analysis of the cultivated microorganisms shows that a consortium of green microalgae, cyanobacteria, and diatoms are typically present in the cultivation system [32]. Harvested and polymer-thickened algae were provided by the system owner (Gross-Wen Technologies, Slater, IA, USA) for HTL processing. Upon receipt, the algal biomass was autoclaved at 121 °C and stored frozen (0 °C). After storage, excess and clarified water was decanted from the slurry. The algal biomass was measured for solids, ash, and elemental content per previously described procedures [33].

The HTL equipment consists of a bench-scale continuous-flow reactor. The experimental process, including the analytical methods to characterize the feeds and products, is described in previous reports [33,34]. The slurry was hydrothermally processed at setpoint conditions of 350 °C, 200 bar (gauge), and liquid hourly space velocity of 4.5 volumes of flow per reactor volume per hour. The HTL products, consisting of biocrude, aqueous phase, residual solids (primarily inorganic elements), and gases, were collected and quantitatively and qualitatively analyzed. Experimental measurements included elemental analysis to measure carbon, hydrogen, nitrogen, oxygen, and sulfur and metals analysis via inductively coupled plasma optical emission spectroscopy (ICP-OES) of feedstock and biocrude, aqueous, and solids products. The gaseous product mixture was quantified using a wet test

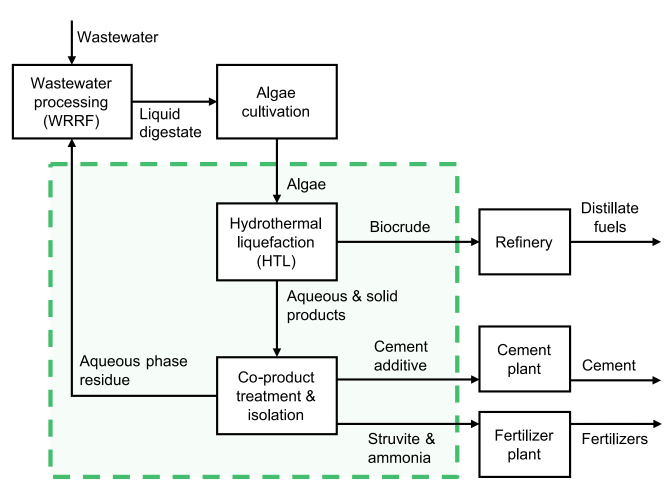

Fig. 1. Flowsheet of process model and analysis boundary.

meter, and its individual components were identified and quantified using an Agilent μ990 gas chromatograph and the OpenLab EZChrom software package.

2.2. Catalytic hydrotreating and quality assessment

The HTL biocrude was upgraded via hydrotreatment to produce a hydrocarbon-rich product, reducing nitrogen, oxygen, and sulfur. Hydrotreatment was completed using a trickle-bed reactor as described previously [35]. Previous determinations for catalyst selection and process conditions have been successfully applied to achieve the best possible outcomes for hydrotreatment [36–39]. The catalyst bed consisted of a pre-zone and two reaction zones. The pre-zone was packed with an inert silicon carbide extrudate to enable mixing and pre-heating of the gas and liquid reagents. The first reaction zone was composed of 4 g of cobalt-molybdenum catalyst supported on alumina (Alfa Aesar #40435, 3.5 % cobalt oxide, 14 % molybdenum oxide). The catalyst was diluted with 20–40 mesh silicon carbide packing material to improve liquid distribution. The second reaction zone contained 4 g of the same cobalt-molybdenum catalyst but instead was diluted with 70–100 mesh silicon carbide to improve surface wetting. Methanol was used as a diluent at 10 vol% to reduce biocrude viscosity and improve flowability. During the hydrotreating reaction, methanol is largely converted to gaseous products (e.g., methane) and removed via the gas–liquid separator. Post-reaction, residual methanol levels in the liquid product were confirmed to be below detection limits using gas chromatography, ensuring that methanol did not interfere with subsequent product quantification or boiling point measurements.

For evaluating the key characteristic properties of SAF, a low-volume testing methodology was performed at Washington State University, Tri-Cities (Richland, WA, USA). The sample was assessed via 2–dimensional gas chromatography and the composition results were used to predict critical quality attributes of the SAF that could be isolated from the hydrotreated sample [40,41]. The upgraded oil was distilled in a lab-scale system at atmospheric conditions to quantify the boiling point distribution. Five fractions were collected and weighed based on the boiling point ranges of 20–85 °C, 85–175 °C, 175–230 °C, 230–290 °C, and > 290 °C.

2.3. Techno-Economic analysis

A techno-economic analysis (TEA) was performed to model and quantify the economic potential and benefits of producing SAF and other fuel products from wastewater-grown algae. Fig. 1 summarizes the flow of processes and materials of the modeled process. The figure also shows the process boundary for material flows and unit operations that are modeled and assessed, emphasizing the sections related to HTL of the biomass and post-treatment of some of the HTL products.

It was assumed that the processing scale of the system was set to match the scale of a WRRF with a treatment capacity of 100 million gallons (379,000 m^3) per day. From the base scale of capacity for the WRRF, it is possible to estimate the rate of effluent flows. Anaerobic digestion was assumed as a treatment method to reduce solids at the WRRF. Anaerobic digestion produces a nutrient-rich liquid effluent that must be further treated. As discussed in the introduction, algae cultivation can be used for nutrient removal. In most WRRF facilities with anaerobic digestion capabilities, approximately 1 % of the wastewater flow becomes liquid digestate [42]. The liquid digestate was assumed to be the sole nutrient source for algae cultivation. The produced algae were considered the main feedstock for HTL. The algal production rate was estimated based on the typical values for nutrient concentrations of nitrogen and phosphorus in the effluent stream of 420 ppm and 66 ppm, respectively [42]. Phosphorus was assumed to be the limiting nutrient for algal growth. All other nutrients, including nitrogen, were assumed to be in sufficient quantity to sustain steady-state cultivation. For baseline calculations, it was assumed that the phosphorus content of the algal biomass was 1 wt%. Variations of the phosphorus content in the algae were examined via sensitivity analysis.

The produced algal biomass was provided to the HTL process as concentrated slurry with 20 wt% solids in water and fed into the HTL process. The gas products from HTL were assumed to be mostly carbon dioxide and emitted to the environment. The aqueous phase products were assumed to be treated with calcium oxide (quicklime) to enable ammonia stripping and recovery. Residual aqueous-phase products were recycled back to the WRRF at no cost. Phosphate was extracted from the solid products and then reacted with the recovered ammonia and an input of magnesium to produce struvite, a high-value fertilizer product. The residual HTL solids, which are rich in inorganic minerals, including aluminum, calcium, silica, and iron, were dried and sold as a cement additive [20]. The HTL biocrude was assumed to be transferred to a refinery in which it was upgraded and distilled to produce several fuel fractions, including gasoline, diesel, and SAF.

The primary element of the TEA was the process model used to approximate the material and energy balances and material transformations within the process boundary. The process model was built in Aspen Plus and has been used in several studies to predict the outcomes for industrial-scale processing of algal biomass via HTL [16,20,26,34,43]. The measured elemental composition of the algal biomass and the HTL products and the experimental yields of HTL products were inputted into an Aspen Plus process model for HTL. The reactor model within Aspen Plus was set to match the experimental processing conditions. The value for liquid hourly space velocity used in experiments (4.5 volumes of flow per reactor volume per hour) was used to estimate the reactor size. Results from the Aspen model were inputted into a TEA model, built in Microsoft Excel, to calculate the break-even selling price or the minimum fuel selling price (MFSP) of SAF and other fuel products.

For hydroprocessing, the theoretical consumption of hydrogen to effectively remove the oxygen, nitrogen, and sulfur from the biocrude was assumed. The process model was fit to the measured yield from the hydrotreatment and distillation experiments. The extraction of phosphate and production of struvite was calculated using previously reported efficiencies. That is, 99.5 wt% of the total phosphorus from the algae was recoverable as phosphate [17] and the phosphate, as the limiting reagent, was 100 % converted into struvite. Magnesium oxide was added to supplement struvite formation. To improve interpretability in the mass balance, struvite was reported in a simplified water-free form ($MgNH_4PO_4$), which excludes the hexahydrate component of struvite ($MgNH_4PO_4 \cdot 6H_2O$). Recoverable ammonium in the HTL aqueous phase exceeds the molar ratio required for struvite formation.

For the economic model, several assumptions were made for material pricing. The cost of algal feedstock transferred to the HTL process was set at zero. Solids at a WRRF are typically a disposal burden that are land-filled or land-applied at a cost to the WRRF [44]. The co-products of struvite and cement materials were sold at market rates of $780/ton [34] and $120/ton [20], respectively. The costs of upgrading the biocrude were estimated by including the cost of transportation to the refinery and the cost of hydrogen for hydroprocessing to remove excess oxygen, nitrogen, and sulfur. The transportation cost was assumed to be $140/$m^3$ of biocrude [20]. For reporting purposes, the produced volume of biocrude was normalized against gasoline gallon equivalents (GGEs) based on lower heating value (LHV). GGE is the amount of fuel it takes to match the energy content of 1 gallon of gasoline. Reporting TEA results in GGE normalizes all products and their values against their respective energy content and facilitates comparison with other alternative fuels. Fixed operating costs for labor were estimated using guidelines from a previous report [45]. Cost of equipment was derived from previous estimations that incorporate vendor quotations and formulaic estimations [43]. A double-declining balance depreciation method was used with a period of 7 years for all machinery and equipment based on a modified accelerated cost recovery system. All cost values were normalized using relevant indices for labor, materials, and equipment to the 2024 cost year. A discounted cash flow rate of return analysis was performed to evaluate the MFSP of the distillate fuel products. The MFSP was obtained by iterating the fuel cost to obtain a net present value of zero for the total economic investment. Table S1 in the supplemental information summarizes other economic assumptions incorporated into the TEA, including assumed prices for commodity inputs.

3. Results and Discussion

3.1. Hydrothermal liquefaction

The provided biomass was processed in a bench-scale, continuous-flow HTL system. Measured properties of the feed such as ash content and elemental characterization of carbon, hydrogen, oxygen, nitrogen, and sulfur, and metals analysis via ICP-OES have been reported previously [16]. Fig. 2 presents the mass distribution of the HTL products of wastewater-grown algae on a dry-weight basis. The yield of biocrude was 26 wt%, which is in range of other results from batch systems [29,46] but is low relative to a reported yield of 40 wt% [47]. However, 44 wt% of the original carbon in the biomass is retained in the biocrude product. The gas yield is relatively low compared to the other products. Only 5 wt% of the carbon is converted to gas, which is mostly (94 vol%) measured as carbon dioxide, with the balance as alkanes with carbon numbers ranging from one to five. Table S2 in the supplemental information shows the complete composition profile. The yield of solid products was 28 wt% of the original biomass, but 21 wt% of the total feed is inorganic material. Generally, inorganic materials are inert during HTL, so the inorganic content predominantly partitions to the solid phase. The solid products retained 12 wt% of the original carbon in the biomass. The carbon content in the solid products can be attributed to large carbonaceous structures that are collected with the solids in the inline filter and to components of the HTL biocrude that adhere to the inorganic solid products. Solvent extraction can facilitate the transfer of carbon in the solids to the biocrude product and will vary with respect to the solvent:solid ratios and solvents selected [48].

The portion of carbon that partitions to the aqueous phase represents an opportunity for additional carbon recovery [49]. Table S3 in the supplemental information reports analysis of the aqueous phase using high-performance liquid chromatography to identify and quantify known components [50]. Additional results reported in the supplemental information include measurements for total nitrogen, total ammonia, chemical oxygen demand, and pH. Detailed analysis shows that 78 wt% of the feed nitrogen partitions to the aqueous phase and 58 wt% of the nitrogen is in the form of ammonia. The recovery of ammonia is important to support fertilizer production as an HTL co-product. Other components of the aqueous phase include volatile fatty acids and oxygenates. The composition profile of the aqueous phase and the mass and elemental balance of the other HTL products were used to inform the Aspen Plus process model and to ensure the model results are fit to the experimental data.

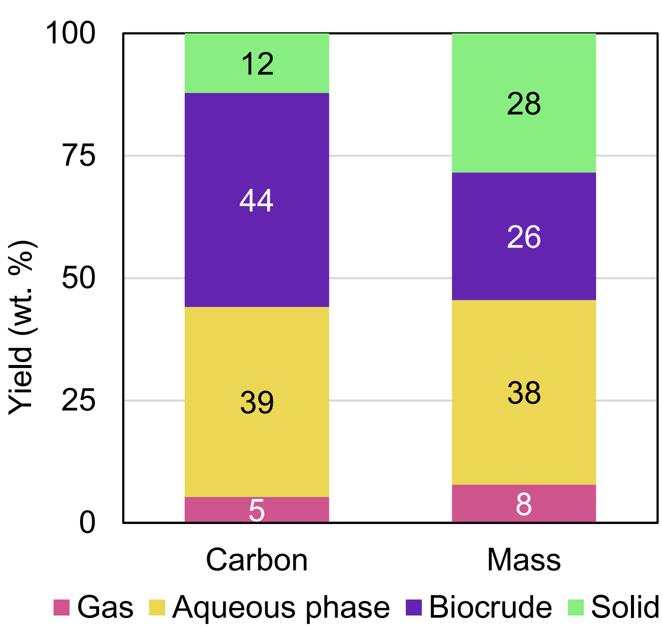

Fig. 2. Carbon yields and mass yields (dry basis) from HTL of wastewater-grown algae.

Table 1 compares the results from ultimate analysis and other key parameters for assessing the quality of HTL biocrude to the values for petroleum crude. The biocrude derived from HTL of wastewater-grown algae has carbon and hydrogen content of 75 wt% and 8.9 wt%, respectively, which is typical of biocrude from HTL of algae [26] and similar to other reports of the composition of biocrude wastewater-grown algae specifically [34]. Compared to petroleum crude, the biocrude has much higher oxygen and nitrogen content at 8.9 wt% and 6.2 wt%, respectively. It is well known that HTL biocrudes and other biomass-produced oils typically have much higher oxygen and nitrogen content when compared to petroleum crude [52]. In spite of the elevated content of oxygen and nitrogen relative to petroleum, hydroprocessing to produce a pure hydrocarbon stream is achievable [36]. The higher heating value (HHV) of biocrude derived from wastewater-grown algae was calculated at 36 MJ/kg using the composition data [53]. The higher content of oxygen and nitrogen in the biocrude reduces the heating value relative to the > 40 MJ/kg HHV expected for most petroleum crude.

ICP-OES was used to quantify metals in HTL products. Of particular interest is the profile of elements in the HTL solids, shown in Table 2. These solids are proposed to produce fertilizer and cement products. The phosphorus in the solids is especially high at 140,000 ppm. The phosphorus is accumulated during the cultivation of the algae and provides a valuable treatment service by removing the phosphorus from the liquid digestate. After HTL, the phosphorus is mostly retained in the solid phase as insoluble phosphate, which can be extracted with acid and then used to produce fertilizer products, as proposed in the process model. The elements of iron, calcium, silicon, and aluminum have value as a cement additive. Calcium and silicon are especially preferred and have been observed in much higher concentrations in other algae samples [20]. Due to the favorable composition of the HTL solids, it is proposed that they can be used as a cement additive. Metal profiles of the feed solids, biocrude, and aqueous-phase products are reported in Table S4 in the supplemental information.

3.2. Hydrotreating and SAF assessment

HTL biocrude has a significant amount of oxygen, nitrogen, and sulfur when compared to petroleum crude, so hydroprocessing or hydrotreatment is used to enable hydrodeoxygenation, hydrodenitrogenation, and hydrodesulfurization, respectively, to minimize the content of heteroatoms and maximize the quality of the finished fuel products. After hydrotreatment, the upgraded fuel was distilled; the

Table 1
Elemental composition and key parameters of biocrude.

Property	Units	HTL biocrude	Petrol crude [51]
Carbon	wt. % (dry, ash-free)	75	83–87
Hydrogen	wt. % (dry, ash-free)	8.9	10–14
Oxygen	wt. % (dry, ash-free)	8.9	0.05–1.5
Nitrogen	wt. % (dry, ash-free)	6.2	0.1–2
Sulfur	wt. % (dry, ash-free)	1.1	0.05–6
H:C mol ratio	–	1.4	1.8–2
Higher heating value	MJ/kg	36	43
Moisture	wt. %	26	–
Ash	wt. %	1	–

Table 2
Inorganic composition of the HTL solids, arranged from highest to lowest measured concentration (only detected metals are reported).

Element	Value (ppm)
Iron	170,000
Phosphorus	140,000
Calcium	98,000
Magnesium	17,000
Silicon	16,000
Aluminum	9,400
Sulfur	3,300
Potassium	3,200
Sodium	2,300
Manganese	1,400
Titanium	1,100
Zinc	850
Barium	820
Chromium	510
Strontium	490
Copper	340
Zirconium	110
Nickel	87

distributions of component fractions are listed in Table 3. Only 15 wt% of the upgraded fuel product was distilled within the typical range for jet fuels (175–230 °C), while the naphtha, diesel, and heavy cuts were 28, 35, and 22 wt%, respectively. The hydrotreated sample was analyzed using 2-dimensional gas-chromatography with a flame ionization detector (GCxGC-FID) to determine the hydrocarbon type distribution and to predict key fuel properties [40,41].

The optimum distillation temperature for the jet fraction was determined to be 175–230 °C using an in-house distillation optimization tool [54]. The cut point is motivated by the density, flash point, and viscosity specification limits. Simulated distillation was also calculated on the hydrotreated biocrude; the jet fraction characterization is shown in Fig. 3.

Fig. 3A presents a detailed hydrocarbon type analysis of the jet fraction. The green shaded regions depict the carbon distribution of an average conventional jet fuel (Jet A, POSF 10325) for comparison [55]. The stacked colored bars represent the carbon distribution of the HTL jet fraction. The average carbon number for the produced jet fraction is 10.8, which is relatively close to that of conventional jet fuel (11.4), as represented by the green line. This similarity suggests that the average carbon number of the HTL jet fraction aligns with that of conventional jet fuel, indicating comparable fuel properties. Overall, the measured fuel consists of 23.0 wt% n-alkanes, 28.7 wt% *iso*-alkanes, 32.3 wt% mono-cycloalkanes, 3.1 wt% poly-cycloalkanes, and 12.9 wt% aromatics, closely resembling the distribution of conventional jet fuel [55].

Fig. 3B displays the predicted key properties of the jet fraction, including surface tension (σ [22 °C]), density (ρ [15 °C]), viscosity (*ν* [-20, −40 °C]), LHV, flash point (°C), DCN, and freeze point (°C). The average predicted values for surface tension, density, viscosity (−20 °C and −40 °C), flash point, and DCN of the sample all lie within the experience range for conventional jet fuel. However, the freeze point is slightly lower and the LHV is slightly higher than the conventional jet fuel range. A lower freeze point is generally advantageous for aviation turbine fuels, as it extends the operational temperature range of the fuel and reduces the risk of wax formation and fuel pump blockages at higher

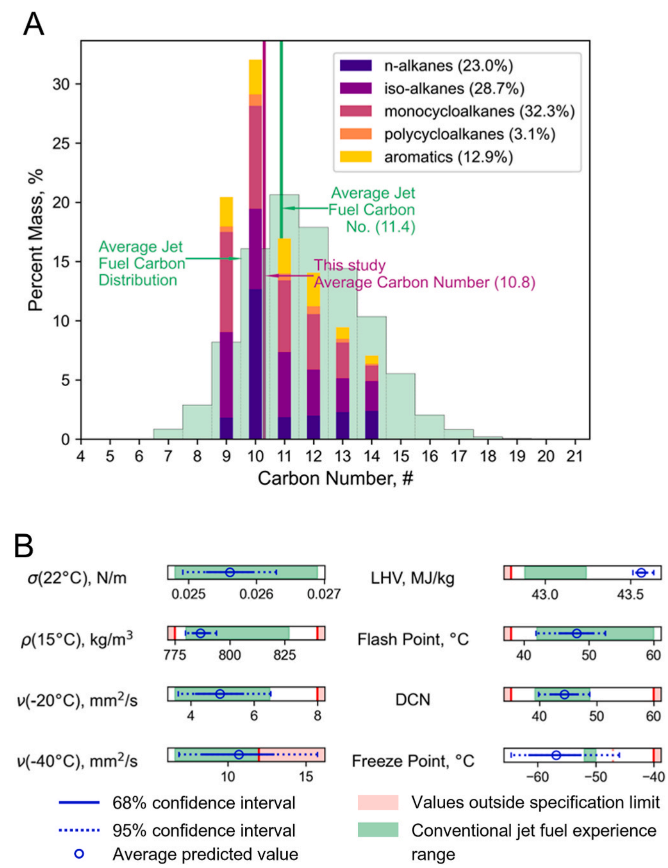

Fig. 3. (A) Carbon distribution of HTL jet fraction and (B) key fuel properties of upgraded biocrude derived from wastewater algae.

altitudes. A higher LHV indicates a greater energy content per unit mass, which potentially can lead to longer flight ranges or reduced fuel consumption. These deviations from the conventional experience range reflect performance improvement characteristics that could offer operational and economic benefits.

3.3. Process and economic Mode

Fig. 4 shows the predicted mass and elemental flows as a Sankey diagram for feedstocks and products for the modeled process. The elemental flows include carbon, hydrogen, nitrogen, sulfur, oxygen, and phosphorus. All inorganic elements are grouped into a single category to represent elements such as iron, phosphorus, calcium, magnesium, silicon, and aluminum, which account for 25 wt% of the elements in the algal biomass. Experimental yields from the HTL and hydrotreatment processing are used to fit the mass and elemental balances. The product yields and elemental balance from HTL are modeled to match the measured yields. The HTL biocrude is upgraded in a refinery to produce distillate fractions of fuels. Hydrogen is added during hydrotreatment, producing distillate fuels that include fractions for gasoline and naphtha, SAF, diesel, and heavy distillates. Modeled values for fractional distillation are fit using the results for atmospheric distillation reported in Table 3. A small fraction (8 wt%) of gases is produced during HTL and has limited value for material or energy recovery as most of the composition is carbon dioxide (94 vol%). The basis for the flow of phosphorus comes from the assumed 1 wt% value of phosphorus in the feedstock algae. The residual HTL solids can be used directly as a cement additive. A fraction of the original biomass carbon (11 wt%) is retained in the solid residue after phosphorus extraction and is assumed to be blended with the cement product. The small amount of carbon has the potential to offer some sequestration benefits to the process, fixing

Table 3
Distillate fractions of hydrotreated HTL biocrude.

Temperature range (°C)	Component description	Fraction collected (wt. %)
<175	Gasoline + naphtha	28
175 – 230	Jet	15
230 – 290	Diesel	35
>290	Heavy distillates	22

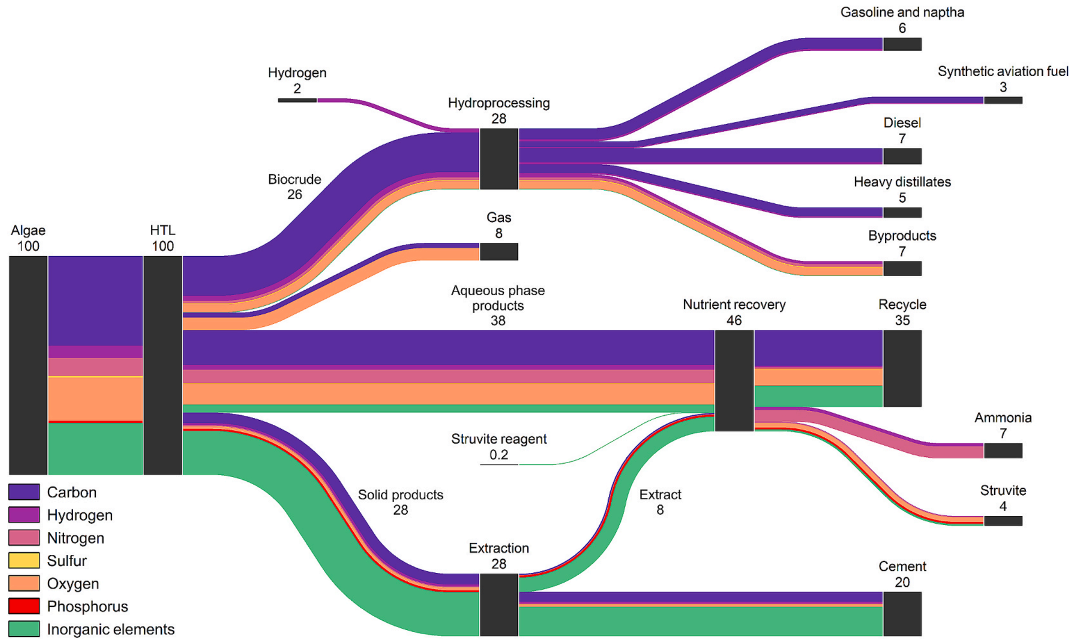

Fig. 4. Sankey diagram showing material and elemental flows (wt. %, water-free basis) across the modeled process.

carbon into a durable good with a long lifetime (>50 years). The full benefit of this carbon storage could be the subject of future investigations. Although some of the original nitrogen in the biomass (5 wt %) is used in the struvite, most of the nitrogen (73 wt%) remains in the aqueous phase. Most of the recovered nitrogen is assumed to be sold as ammonia, but the cost contributions from ammonia are minor when compared to other co-products. Non-utilized carbon organics in the aqueous phase are recycled back to the headworks for the WRRF.

The primary metric for the TEA is the MFSP of the SAF and other fuel products. The production of SAF from wastewater-grown algae has been demonstrated experimentally at laboratory scale, but the potential selling price of SAF and other biofuel products will strongly influence acceptance into fuel markets. The proposed system and system boundary for the TEA are described in Section 2 and are depicted in Fig. 1. Economic assumptions are also described in Section 2 and the supplemental information. Table 4 shows the calculated MFSP of $9.04 of all fuel products, normalized on a GGE basis. The costs for HTL to produce biocrude, the upgrading of biocrude via hydrotreatment, and the post-processing of the other HTL products to yield struvite, cement, and ammonia are also shown in Table 4. The credits from the sale of struvite and cement additive are also included. The calculated value of ammonia is relatively small compared to the value of the other products. As the wastewater-grown algae is provided at zero-cost to the HTL process, it is considered a cost-advantaged biomass, unlike cultivated algae, which may cost >$600/ton [56]. The major cost contributor to the MFSP is the production of biocrude from algae biomass via HTL, which incorporates the majority (59 %) of the capital and operating expense for the overall

Table 4
MFSP and cost distribution of SAF production from wastewater-grown algae.

Production area	Cost distribution ($/GGE, 2024$)
Biocrude production	$6.02
Biocrude hydrotreatment	$1.40
HTL aqueous and solid phase treatment	$1.73
Balance of plant	$1.00
Byproducts credits (supplementary cementitious materials)	−$0.19
Byproducts credits (struvite)	−$0.92
TOTAL	$9.04

process. The estimated capital cost of the HTL system is $16 million for the current scale of 25 dry tons per day. Byproducts credits in the form of supplementary cementitious materials (cement additives) and struvite are also included in the calculation for the MFSP. A combined credit for both struvite and cement is realized, assuming that phosphorus is recovered from the solids first and the remaining solids are a cement product. Although a smaller fraction of struvite is produced relative to the cement additive, the struvite has a much higher potential value ($780/ton) when compared to the cement additive ($120/ton). TEA results, including total capital investment, variable and fixed costs, and revenue from byproducts, are reported in Table S5 of the supplemental information.

A sensitivity analysis was performed to understand the impact of parameters of plant scale, capital cost, internal rate of return (IRR), phosphorus content, feedstock cost, ash content, cement additive price, struvite price, and biocrude yield on the MFSP of SAF and other fuel products. The parameters are broadly grouped into three categories: plant, feedstock, and product. Fig. 5 shows the results of the sensitivity analysis on the MFSP. The plant-specific parameters, which include plant scale and capital cost, have the highest impact on the MFSP.

The scale of the HTL plant is determined by the availability of the feedstock and has a major influence on the economics of the process. Increasing scale reduces costs, and can be achieved by increasing the scale of wastewater treatment (and algae production) or by blending algae with other wastewater solids available as blendstocks, such as anaerobic digester solids (biosolids) or primary and secondary sludges [16]. The scale of feedstock supply is influenced by the total amount of phosphorus available for algae cultivation, determined by the treatment capacity of the adjacent WRRF and the concentration of phosphorus in the wastewater. It is assumed that an average phosphorus concentration in the wastewater stream provided for cultivation is 66 ppm [42], but in reality the phosphorus concentration can range from half as much (35 ppm, [57]) to over three times as much (200 ppm, [58]) and will depend on the source and preceding treatments.

In the presented sensitivity analysis, the yield of algae per mass phosphorus in the algae cultivation system is varied. The phosphorus content of the algae biomass can vary from 0.5 wt% to over 6 wt% [59]. Phosphorus content is doubled or halved as a sensitivity parameter, which corresponds to changes in plant scale of 12.5 and 50 dry tons per day, respectively. The variation in phosphorus content of the algae

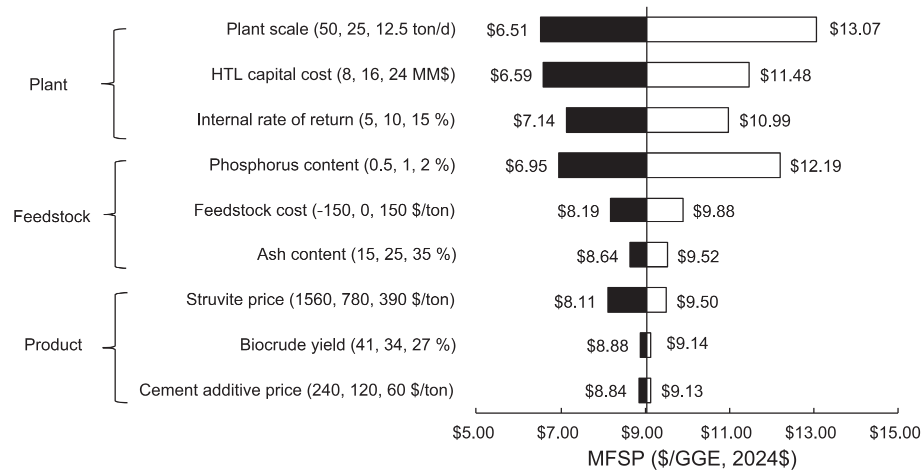

Fig. 5. Sensitivity analysis of SAF production from HTL of wastewater-grown algae.

biomass influences the volume of fertilizer product that is generated and sold for additional revenue. Varying the scale of biomass availability by modifying the phosphorus content of the algae biomass results in a lower MFSP at the 12.5 dry tons per day scale and a higher MFSP at the 50 dry tons per day scale.

Capital cost is almost equally impactful compared to plant scale, as a significant investment is needed to establish HTL processing. For early-stage engineering estimates, accuracy is expected to be ± 50 %, which is assumed for the sensitivity analysis. For the proposed estimates presented in this paper, the capital costs are still preliminary, representing an optimistic and hypothetical design [43].

Projecting costs for capital projects using net present value analysis is an important consideration for how the MFSP is calculated. The IRR selected for the financial modeling influences the calculated MFSP. A standard of 10 % is selected as the baseline, which is common to other biorefinery type processes [60]. Sensitivity of IRR by ± 50 % from the baseline can influence MFSP by at least 27 % ($2.44/GGE). Other parameters such as feedstock cost and struvite selling price influence the MFSP by <$1.00/GGE. The content of ash in the feedstock, the yield of the biocrude product, and the selling price of the cement additive have less influence on the final MFSP, adjusting cost at most by $0.39/GGE.

As observed in the sensitivity analysis, the scale of the HTL plant has the most significant impact on the final MFSP. Scale can be increased by increasing the availability of algae biomass, either by increasing the amount of phosphorus available for algae cultivation or by increasing the yield of algae for a fixed amount of phosphorus. Alternatively, scale can be increased by blending the algal feedstock with other biomass sources, including organic solids that are present at the WRRF. Assuming similar outcomes for product yields, the current plant could achieve MFSP values of <$5.00/GGE, as shown in Fig. 6, if the process is scaled to > 100 tons per day. The scale-up benefits from known principles for economy of scale, resulting in a reduced MFSP. A previous study showed that blending wastewater-grown algae with biosolids has the potential to boost biomass availability and further reduce the MFSP. For instance, a WRRF of 100 MGD capacity could produce 52 tons per day of biosolids in addition to 25 tons per day of algae biomass [16]. Additionally, blending with other wet-waste feedstocks such as non-residential food waste could boost the processing scale of the HTL facility by another 10–60 % relative to the available wastewater solids being processed [43]. Besides biosolids and food wastes, blending with other regional biomass sources such as animal manures and fats, oils, and grease could boost the processing scale beyond 100 tons per day [61]. Further reduction in the MFSP is achievable through incentive programs funded by the US government for US fuel producers. The potential credits could reduce the MFSP by as much as $2.74/GGE [16].

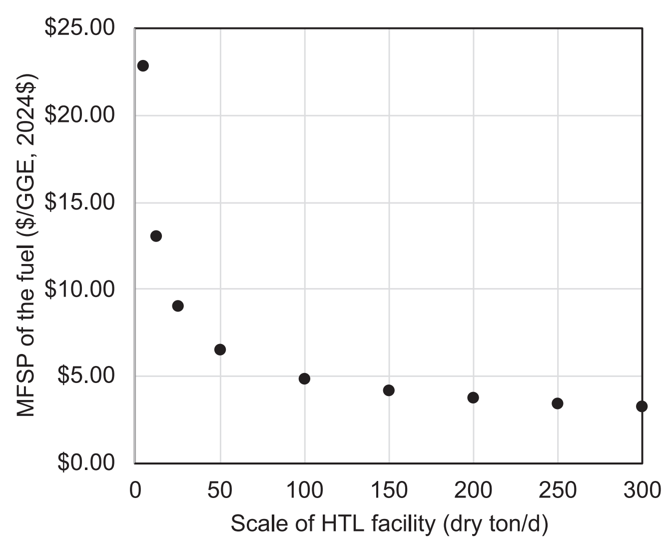

Fig. 6. MFSP with respect to the scale of the HTL plant.

4. Conclusions

The presented study models the cost and experimentally determines the quality of SAF produced from wastewater-grown algae. HTL processing yielded mass and carbon recoveries of 26 wt% and 44 wt%, respectively. The yield and recovery values demonstrate the potential to upgrade biomass materials that would otherwise be used as a fertilizer product or possibly landfilled. The process model demonstrated that when taken together, 57 wt% of the original biomass can be used to produce a variety of useful products, including both solid struvite and liquid ammonia fertilizers, a cement additive material, and liquid fuel. The quality of the SAF fraction of the fuel produced met the expected experience ranges for conventional petroleum fuels. As demonstrated in this study, HTL can be advantageous for SAF production from wastewater-grown algae as the conversion method produces an appropriate balance of n-alkanes, isoalkanes, cycloalkanes, and aromatics, which influences critical fuel properties such as viscosity, surface tension, and freeze point. The TEA shows that the current benchmark for MFSP is relatively high ($9.04/GGE) when compared to petroleum fuels, but improvements in algae production and plant scale can reduce costs to be more economically competitive (<$5.00/GGE). To date, the presented work at laboratory scale represents a promising pathway for the production of valuable products from wastewater-produced algae.

Nonetheless, additional development work is necessary to advance the proposed pathway through process scales and technology readiness. Continued scale-up of the proposed pathway will further validate the performance results presented herein. Detailed cost estimations using vendor quotations coupled with market analysis of the products will further refine the TEA.

CRediT authorship contribution statement

Abhishek Kumar: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Jacob D. Watkins:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Dylan Cronin:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Andrew J. Schmidt:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Daniel M. Santosa:** Writing – review & editing, Formal analysis, Data curation. **Zhibin Yang:** Data curation, Formal analysis, Visualization, Writing – review & editing. **Joshua Heyne:** Data curation, Formal analysis, Visualization, Writing – review & editing. **Peter J. Valdez:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2025.101096.

Data availability

Data will be made available on request.

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