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Techno-economic and life cycle assessment of wet waste hydrothermal liquefaction with different biocrude upgrading strategies

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Hydrothermal liquefaction (HTL) emerges as a promising technology for producing renewable, low-carbon biofuels from wet wastes, offering a sustainable alternative to fossil fuels. This process is particularly advantageous because it minimizes the need for feedstock drying and allows for the implementation of customized upgrading strategies to meet diverse fuel specifications. A comprehensive study was conducted to evaluate the economic and environmental impacts of using HTL to convert various wet wastes into biofuels. The research involved techno-economic analyses and life cycle assessments of the HTL process integrated with different and biocrude upgrading strategies. Aspen Plus models and experimental data from lab-scale systems were used, with a focus on three feedstock types (sewage sludge, manure, and food waste) and three upgrading strategies for marine fuel, sustainable aviation fuel, and renewable diesel production. For marine fuel, biocrude underwent mild hydrotreating, whereas for sustainable aviation fuel and renewable diesel production, the biocrude was necessarily subjected to full hydrotreating and fractionation. The results revealed that feedstock type and process choice significantly influence economic and environmental outcomes. This research highlights HTL's potential for advancing renewable fuel production, contributing to national energy security, diversification, and emission reduction.

Sustainability spotlight

Humankind produces two billion tonnes of waste currently, which could rise by 70 percent by 2050. Hydrothermal liquefaction is an energy efficient and economically feasible technology to convert organic waste into transportation fuel, which can simultaneously diversify energy supplies, make affordable renewable energy, reduce emissions and landfill demand. In response, this work offers a comprehensive analysis evaluating the economic and environmental impacts of producing sustainable aviation fuel, renewable diesel and marine fuels from sewage sludge, food waste and swine manure, demonstrating how feedstock and upgrading strategies influence outcomes. This work aligns directly with UN and global Sustainable Development Goals related to affordable and clean energy, responsible consumption and production, and climate action.

1 Introduction

Wet wastes, including food waste, sewage sludge, and animal manure, present a significant environmental challenge in the United States and globally. Effective waste management practices are crucial, yet they vary widely in terms of cost and feasibility, often influenced by local regulations, technological availability, and economic factors. Adopting more waste management solutions can yield long-term financial and ecological advantages. The high moisture content inherent in wet waste complicates the application of conventional waste-to-energy technologies like incineration, pyrolysis, and gasification. These methods require significant energy input to process wet materials, making them less viable both economically and environmentally.

However, hydrothermal liquefaction (HTL) can efficiently convert high-moisture wet wastes into biocrude at high pressures of 5–20 MPa and high temperatures of 250–400 °C.[1] HTL exploits the properties of superheated water to reduce mass transfer resistance. Meanwhile, the high pressure also enables higher penetration of the solvent into the biomass structure to facilitate the fragmentation of biomass molecules.[2] The nature of the process allows for feedstock with high moisture content; therefore, a wide range of materials can be subjected to HTL for biocrude production. HTL studies have been conducted for various feedstocks, including woody biomass,[3,4] forest residues,[5,6] agricultural residues,[7] municipal wastes, sewage sludge,[8] manure,[7] algae,[9] and plastic.[10,11] The biocrude

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produced from the HTL process is a dark, viscous liquid with a higher heating value, lower oxygen content, and greater stability than the bio-oils from other biomass liquefaction processes (*e.g.*, fast pyrolysis). However, despite its remarkable characteristics, biocrude may not be capable of meeting the requirements for drop-in transportation fuels because of its high viscosity, high heteroatoms content, low hydrogen-to-carbon ratio, and relatively high final boiling point. Hence, biocrude upgrading is necessary—especially hydroprocessing, which is a catalytic chemical process that occurs at high temperatures (350–420 °C) and pressures (8–13 MPa).

To date, studies on HTL biocrude upgrading remain limited in literature. Most research in this field has focused on the following areas: (1) investigations of hydrotreating catalysts and operating conditions, (2) the design of hydrotreating reactors and process flowsheets, (3) co-processing with existing refinery infrastructure, and (4) challenges associated with biocrude derived from different types of feedstock. Specifically, research has delved into diverse catalysts and conditions, including Pt/Al_2O_3, HZSM-5,[12] and sulfided catalysts like NiMo and CoMo.[13,14] Innovations in reactor designs, such as continuous slurry and fixed-bed reactors, aim to mitigate issues like coking. Co-processing biocrude with existing refineries offers economic benefits and enhanced efficiency but poses risks, such as catalyst deactivation and adverse effects on fuel quality.[15–20]

Much upgrading work has been performed with biocrudes derived from algae,[21–24] sewage sludge,[25,26] and animal manure.[27] Different feedstocks produce biocrude with different properties (*e.g.*, in terms of composition, heteroatom characteristics, and metal content), leading to distinct challenges. Other works found that heteroatoms in sludge biocrude are easier to remove than those in algal biocrude, whereas nitrogen removal from algal biocrude is particularly challenging.[28,29] Along the same line, Pacific Northwest National Laboratory upgraded five different types of biocrude in a continuous bench-scale hydrotreater with either a sulfided NiMo or a CoMo catalyst. Deep hydrodenitrogenation (HDN) after whole-crude hydrotreating was found to be necessary for meeting the N content requirement for sustainable aviation fuel (SAF).[30]

In addition to the experimental studies described above, a few techno-economic analyses (TEAs) and life cycle analyses (LCAs) have been conducted on liquid biofuels produced *via* HTL from lignocellulosic biomass,[31] algae,[32] and municipal solid waste.[33] However, each HTL conceptual plant is designed to produce a specific fuel from a single feedstock, making cross-comparisons of TEA results challenging due to differing economic assumptions and plant scales. In our previous work, TEAs of sludge HTL for diesel[34] and SAF production[8] and of manure HTL for marine fuel[35] and diesel[36] were performed with different HTL plant boundaries, process assumptions, and HTL aqueous phase treatments. For example, in HTL for marine fuel,[35] the HTL plant scale is assumed to be 1000 metric tons per day, whereas other studies assume that it is 100 metric tons per day, with a centralized upgrading plant. With limited supplies of wet waste and biomass feedstocks and strong demand across different transportation sectors, disagreement could arise over how these resources would best be used, and which fuels should receive priority. To answer such complex questions, comprehensive yet comparable TEAs should be conducted for the various HTL-based pathways for marine fuel, diesel, and SAF produced from different feedstocks.

To the best of our knowledge, the present research constitutes the first attempt to evaluate and compare three upgrading strategies targeting the three most common types of fuel (marine, diesel, and jet) derived from wet waste (specifically, sludge, manure, and food waste). Specifically, detailed Aspen Plus process models were developed on the basis of the experimental data collected from the continuous flow reactor system. This TEA/LCA study contributes to scientific literature by offering a comparative assessment of different feedstocks and biocrude upgrading options targeting different finished fuels. The aim of this comprehensive comparison is to guide researchers and industry stakeholders on opportunities and future research needed for alternative, low-cost biofuel options for the aviation, on-road transportation, and maritime industries.

2 Methods

2.1 Feedstock selection and characteristics

Wet waste resources suitable for HTL typically include animal manure, wastewater sludge, food waste, and inedible fats, oils, and grease (FOG). FOG include used cooking oil (yellow grease), trap (brown) grease, and animal fats. Notably, FOG is extensively utilized in various technical applications for biofuels and has become a standardized, marketable product with significant economic value. In this study, we focused on the utilization of sludge, manure, and food waste. According to the 2023 Billion-Ton Report, the current or near-term supply of total wet waste resources amounts to approximately 622 million tons annually (71 million dry tons, excluding FOG), with roughly 45% of this waste being landfilled.[37] The remaining 55% of wet waste is disposed of through costly conventional waste management methods, such as composting, incineration, drying for fertilizer/land application, or aerobic digestion. Given the high cost associated with conventional waste management methods and landfilling, HTL can potentially impose a "tipping fee" for different types of waste. Moreover, the potential transportation costs of collecting waste at the scale of 100 dry metric tons per day were considered in the analysis in this study. We used a blend of 50% primary and 50% secondary sludge from Great Lakes Water Authority in Detroit, MI, swine manure from a pig farm in Indiana, and food waste from local dining facilities in Washington State to represent the typical composition of sludge, swine manure, and community food waste, respectively. Table 1 presents the feedstock characteristics for the model, and the potential waste tipping fees and transportation costs are detailed in the SI.

2.2 Process model and conceptual design of various upgrading scenarios

The development of detailed process models for HTL plants with various biocrude upgrading options is essential for

Table 1 Wet waste characterization and experimentally measured HTL reactor performance

Parameter	Sewage sludge	Swine manure	Food waste
Ultimate composition, dry, wt%			
C	44.1	46.9	51.0
H	6.2	6.2	7.5
O	28.0	30.4	33.9
N	5.4	3.4	3.3
S	1.1	0.6	0.2
Ash	15.3	12.5	4.1
P	1.9	1.4	0.4
Proximate composition, dry ash free, wt%			
Carbohydrates	19.6	42.9	48.4
Lipid	40.4	35.4	32.8
Protein	40.0	21.7	18.9
HTL product selectivity, dry ash free, wt%			
Biocrude	44	49	46
Aqueous-phase product	31	21	34
Gases	16	25	18
Solids	9	5	2
Biocrude properties			
H/C (mol mol^{-1})	1.6	1.7	1.8
O (wt%, dry)	4.7	13.4	10.6
N (wt%, dry)	4.8	4.3	4.0
S (wt%, dry)	1.2	0.6	0.0
LHV (Btu lb^{-1})	16 900	15 200	16 300

accurately quantifying process yield, raw materials, and energy consumption. An in-house 110 dry ton per day waste HTL process model[8,34] was leveraged and further refined to process different types of waste (*e.g.*, sewage sludge, animal manure, and food waste). The model was built in Aspen Plus on the basis of bench-scale experimental data from Pacific Northwest National Laboratory, as summarized in Table 1. Here, the HTL reactor was modelled as a yield reactor in Aspen Plus with various model components defined based on GC-MS data of HTL products, of which the component selectivity was modified based on the experimentally measured biocrude, aqueous-phase, gas and solid product selectivity and their elemental analysis results. The complete data set is available in Appendix Tables A.1 to A.4 of Snowden-Swan *et al.*,[8] which includes the indices for WW06, WW15, and WW21 for the selected sludge, swine manure, and food waste, respectively, in this work. Detailed descriptions of this HTL process and the model development can be found in SI.

A centralized biocrude upgrading plant model (approximately 3000 barrels of biocrude per day) with different upgrading options was developed in Aspen Plus on the basis of rigorous process models and lab-scale continuous flow system experimental data. To account for the diverse properties of biocrude obtained from different wet wastes, or even from wastes of the same type but with significantly different compositions, a guard bed was utilized for a pretreatment step prior to the main hydrotreating process. The primary function of the guard bed was to eliminate harmful impurities, such as metals and particulate matter, thereby protecting the main catalyst bed from deactivation and fouling. This would also enhance the conversion and quality of the hydrotreating oil. Fig. 1 shows the process flowsheet diagram of the biocrude upgrading plant for marine, biodiesel, and SAF productions. For marine biofuel production, the upgrading strategy included mild hydrotreating to remove the heteroatoms and lower the total acid number to meet fuel standards as well as using the whole distillates without fractionation as marine fuel. For SAF and renewable diesel production, the HTL biocrude was fully hydrotreated for the removal of heteroatoms, followed by fractionation into naphtha, jet, and heavy diesel/residue as well as hydrocracking of residue and/or heavy diesel. Finally, for the combined jet fraction from both hydrotreating and hydrocracking, a deep HDN process was applied to remove enough nitrogen to bring the biocrude's nitrogen concentration below 2 ppm, which is the upper limit for SAF. Tuning the distillation column and hydrocracking operation can maximize the production of SAF or renewable diesel. Table 2 summarizes the operating conditions of hydroprocessing reactors, and fuel selectivity can be found in Fig. 1 for each upgrading strategy.

2.3 Techno-economic analysis

TEA was conducted on the basis of established economic assumptions, specifically the "*n*th plant" assumption that multiple plants are already operational. This method does not consider special financing, equipment redundancies, large contingencies, or extended startup times. The analysis included a process model and an economic model, with mass and energy balances calculated from the detailed process model. Capital and operating costs were estimated from the balances and used in a discounted cash

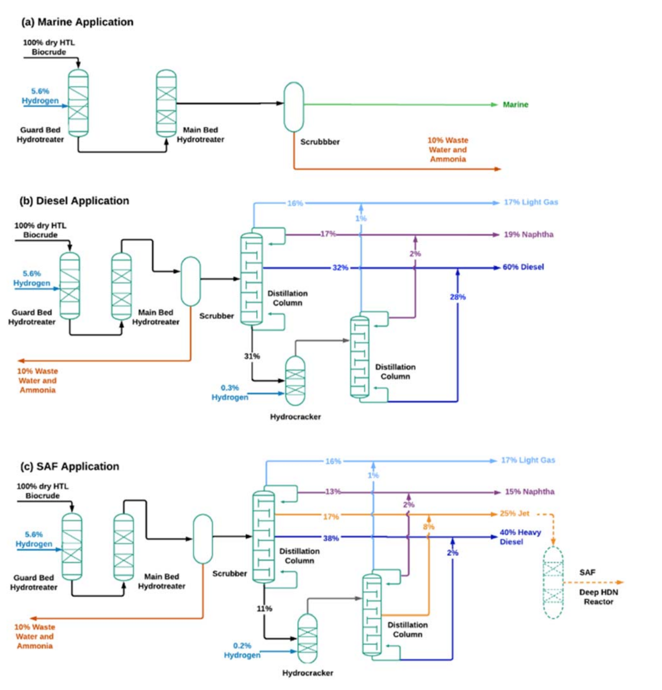

Fig. 1 Different biocrude upgrading designs for marine fuel (a), diesel fuel (b), and SAF (c) production. HTL = hydrothermal liquefaction; HDN = hydrodenitrogenation; SAF = sustainable aviation fuel.

Table 2 Operating conditions and performance targets of hydroprocessing reactors

	Guard bed hydrotreater	Main bed hydrotreater	Hydrocracker	Deep HDN reactor
Catalyst	$CoMo/Al_2O_3$	$NiMo/Al_2O_3$	NiMo/Zeolite	$NiMo/Al_2O_3$
Temperature (°C)	300	400	418	400
Pressure (bar)	69	104	69	108
WHSV[a] (h^{-1})	0.72 (1.00)	1.02	1.00	0.50
O in product (wt%)	N/A	0.2–1.0	Trace	Trace
N in product (wt%)	N/A	0.05–1.6	Trace	<2 ppmw
S in product (wt%)	N/A	<0.03	Trace	Trace
Residual conversion (%)	N/A	N/A	~100%	N/A
Liquid oil yield (wt/wt dry feed oil)	82–85%		96–98%	95%
Application	Marine, diesel, SAF	Marine, diesel, SAF	Diesel, SAF	SAF

[a] A high WHSV value shown in parentheses represents marine application; a sensitivity study was conducted for marine application regarding WHSV. Abbreviations: HDN = hydrodenitrogenation; SAF = sustainable aviation fuel; ppmw = parts per million by weight; WHSV = weight hourly space velocity.

flow analysis to determine the minimum fuel selling price (MFSP) required to achieve a 10% internal rate of return with a net present value of zero. All costs were adjusted to 2020 U.S. dollars. The MFSP was measured in dollars per gasoline gallon equivalent (GGE), with a lower heating value basis for gasoline (116 090 Btu gal^{-1}) sourced from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.[38] Detailed economic and pricing assumptions can be found in the SI.

2.4 Life-cycle analysis

LCA was conducted to evaluate the greenhouse gas (GHG) emissions, criteria air pollutants (CAP) emissions, and water consumption of renewable fuels produced from HTL of wet wastes. The results are reported based on 1 MJ of end-product fuels produced and consumed. The research and development version of the GREET model[38] was used to evaluate these environmental impacts. GHG impacts, including the feedstock-to-fuel supply chain CO_2, CH_4, and nitrous oxide (NO_x) emissions, were estimated according to their respective 100-year global warming potentials (1, 29.8, and 273), across the entire supply chain of fuel production from HTL of wet wastes. CO_2 emissions from conversion and eventual combustion of the carbon in the wet wastes were considered biogenic CO_2 emissions. They were considered carbon neutral and were not explicitly tracked in the calculations.[39]

Waste feedstock must be properly managed and disposed of to ensure regulatory compliance and minimize environmental impact. Waste management generates GHG and CAP emissions, which are avoided when the waste is diverted to renewable fuel production. The avoided business as usual (BAU) emissions (also known as counterfactual emissions) were therefore accounted for as GHG and CAP avoidance credits (*i.e.*, negative emissions) in the LCA results.

This study produced estimates of the avoided counterfactual emissions representing those from a weighted average of typical BAU management practices in the United States. Four management practices were considered for food waste: landfilling (56%), anaerobic digestion (28%), incineration (12%), and composting (4%). Anaerobic digestion was modeled as the counterfactual management practice for sludge because it was reported to be the most popular sludge treatment technology in wastewater treatment plants.[40] In this process, biogas generated from sludge is burned to meet on-site thermal demand, and the excess biogas is flared.[41] For swine manure, BAU management was modeled as a weight average of the following systems: deep pit (66%), liquid/slurry (13%), anaerobic lagoon (11%), and pasture (10%). The life cycle emissions and water consumption for BAU waste management can be found in the SI.

Fuel yields and material and energy consumption were based on the process model. HTL solids were considered to be landfilled, and 80% of the embedded carbon was assumed to be sequestered.[36,42] Wastewater discharge from the HTL facility has a high chemical oxygen demand (COD) concentration. Therefore, the energy and materials required to treat the high-COD waste were also included in the LCA.

3 Results and discussion

3.1 Process performance

Table 3 presents a comprehensive overview of process performance indicators, encompassing fuel production, finished fuel distributions, and energy and carbon efficiencies. Notably, the biocrude upgrading methodology exerted a greater influence on the finished fuel distributions than did the type of feedstock. For instance, only small variations in the finished fuel distributions could be observed across all HTL SAF scenarios, at approximately 16–24% for naphtha, 51–59% for diesel, and 25–30% for jet fuel. In all renewable diesel scenarios, renewable diesel predominated the finished fuel output, accounting for approximately 76–85%. Furthermore, HTL demonstrated relatively high energy and carbon efficiencies across diverse waste types, averaging 74–78% and 58–63%, respectively. Notably, however, the feedstock type did not affect the process efficiency, with lower efficiencies observed in feedstocks characterized by high ash and heteroatom contents. By contrast, compared with diesel and SAF applications, the marine application exhibited slightly higher efficiencies owing to reduced hydrotreatment severity.

3.2 Total capital investment

Capital investment for all of the upgrading scenarios with different feedstocks is presented in Table 4, with detailed

Table 3 Process performance summary for different cases[a]

Performance measures		SHTL_SAF	SHTL_RD	SHTL_M	MHTL_SAF	MHTL_RD	MHTL_M	FWHTL_SAF	FWHTL_RD	FWHTL_M
Total fuel production, lb h^{-1}		27 286	27 384	28 259	30 524	30 539	30 996	33 940	34 011	34 389
Fuel yield, %		76.0	76.2	78.7	75.7	75.7	76.8	78.7	78.9	79.8
Energy in	Biocrude, MMBtu h^{-1}	550.7	550.7	550.7	549.3	549.3	549.3	615.8	615.8	615.8
	Natural gas, MMBtu h^{-1}	101.0	86.0	87.1	173.5	162.5	159.4	203.7	188.2	185.2
	Electricity, kW	4713.6	4797.5	4497.9	4728.9	4427.9	3661.1	5025.1	4943.3	4028.5
Energy out	Diesel, MMBtu h^{-1}	258.2	389.0		288.9	431.9		374.1	540.3	
	Naphtha, MMBtu h^{-1}	94.8	122.9		133.2	124.0		98.5	97.2	
	Jet, MMBtu h^{-1}	154.4			140.4			162.3		
	Marine fuel, MMBtu h^{-1}			523.1			565.8			638.3
Energy efficiency, %, LHV		74.2	76.5	78.3	74.5	74.9	77.1	74.4	76.1	77.0
Carbon efficiency, %		58.2	58.2	59.7	62.7	62.6	63.1	62.4	62.4	62.7

[a] SHTL = sludge hydrothermal liquefaction; MHTL = manure hydrothermal liquefaction, FWHTL = food waste hydrothermal liquefaction; SAF = sustainable aviation fuel; RD = renewable diesel; M = marine fuel; MMBtu = 1 million British thermal units; LHV = lower heating value.

assumptions for capital cost estimates provided in Table S1. Across all sludge HTL cases, the total capital investment for the three upgrading scenarios was as follows, in ascending order: SHTL_M (sludge HTL for marine fuel) < SHTL_RD (sludge HTL for renewable diesel fuel) < SHTL_SAF (sludge HTL for SAF). Notably, SHTL_SAF demonstrated the highest total capital investment, incorporating full hydrotreating guard bed and main bed reactors, distillation columns, a hydrocracking

Table 4 Key process performance variables and cost worksheet (all costs are presented in 2020 U.S. dollars)[a]

Fuel options	Marine fuel application			Renewable diesel application			SAF application		
Feedstocks	Sludge	Manure	Food waste	Sludge	Manure	Food waste	Sludge	Manure	Food waste
Pathway index	SHTL_M	MHTL_M	FWHTL_M	SHTL_RD	MHTL_RD	FWHTL_RD	SHTL_SAF	MHTL_SAF	FWHTL_SAF
Capital costs, $ million									
HTL plant									
Total purchased equipment cost (TPEC)	20.52	22.46	19.47	20.52	22.46	19.47	20.52	22.46	19.47
Total capital investment (TCI)	40.46	44.63	38.76	40.46	44.63	38.76	40.46	44.63	38.76
TCI/TPEC	1.97	1.99	1.99	1.97	1.99	1.99	1.97	1.99	1.99
Centralized upgrading plant									
Total purchased equipment cost (TPEC)	69.99	58.17	60.22	86.05	88.67	102.19	87.10	88.09	107.97
Total capital investment (TCI)	139.10	116.30	120.37	171.53	176.96	203.60	173.67	175.70	215.38
TCI/TPEC	1.99	2.00	2.00	1.99	2.00	1.99	1.99	1.99	1.99
Operating costs, $ per GGE									
Potential feedstock credits	−1.70	−1.29	−0.58	−1.92	−1.25	−0.58	−1.93	−1.26	−0.58
Natural gas	0.07	0.13	0.14	0.08	0.12	0.14	0.09	0.14	0.15
Catalyst & chemicals	0.36	0.43	0.16	0.42	0.43	0.17	0.42	0.44	0.17
Electricity	0.07	0.20	0.07	0.08	0.21	0.12	0.08	0.21	0.12
Waste disposal	0.94	0.86	0.79	1.06	0.83	0.79	1.07	0.84	0.80
Biocrude transportation cost	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Total variable operating cost without feedstock credits	**1.54**	**1.72**	**1.26**	**1.74**	**1.70**	**1.32**	**1.77**	**1.73**	**1.34**
Total variable operating cost with feedstock credits	**−0.16**	**0.44**	**0.68**	**−0.18**	**0.45**	**0.74**	**−0.17**	**0.47**	**0.76**
Fixed operating costs	**1.03**	**1.07**	**0.92**	**1.21**	**1.10**	**1.00**	**1.22**	**1.11**	**1.01**
Total operating cost without feedstock credits	**2.57**	**2.79**	**2.18**	**2.95**	**2.80**	**2.32**	**2.99**	**2.83**	**2.36**
Total operating cost with feedstock credits	**0.87**	**1.50**	**1.60**	**1.03**	**1.55**	**1.74**	**1.05**	**1.58**	**1.77**
Capital costs	**1.72**	**1.81**	**1.47**	**2.12**	**2.02**	**1.76**	**2.14**	**2.03**	**1.80**
MFSP without feedstock credits	4.28	4.60	3.65	5.07	4.82	4.08	5.13	4.87	4.16
MFSP with feedstock credits	2.58	3.32	3.08	3.15	3.56	3.50	3.20	3.61	3.58

[a] SHTL = sludge hydrothermal liquefaction; MHTL = manure hydrothermal liquefaction, FWHTL = food waste hydrothermal liquefaction; SAF = sustainable aviation fuel; RD = renewable diesel; M = marine fuel; TPEC = total purchased equipment cost; TCI = total capital investment; GGE = gasoline gallon equivalent; MFSP = minimum fuel selling price.

reactor, and deep HDN reactors. The installation of deep HDN reactors represented approximately 3.84% of the total capital investment. However, because kerosene/distillate was sent to the deep HDN reactor before it was sent to the hydrocracker in the SHTL_SAF case, the mass flow rate to the hydrocracker decreased by 65 wt%, resulting in a lower hydrocracker equipment cost. Overall, there was only a $1.05 million capital cost difference between SHTL_SAF and SHTL_RD. By contrast, SHTL_M exhibited the lowest total capital investment because it only required mild-condition hydrotreating reactors to remove heteroatoms in the biocrude. Without additional capital costs associated with hydrocrackers and distillation columns, the capital cost of SHTL_M was approximately 19% lower than that of SHTL_RD. Furthermore, the manure and food waste HTL exhibited a similar trend of the total capital investment increasing with the process complexity, while the impact of feedstock type on total capital investment is not significant.

3.3 Operating costs

The operating costs evaluated included labor costs, materials and feedstock costs, utility costs, and disposal costs. Detailed information regarding estimated variable operating costs, such as those related to catalysts, feedstocks, utilities, and disposal for the HTL pathways, is listed in Table S2. Variable operating costs are determined on the basis of the raw materials, waste-handling charges, and by-product credits incurred during the process operation.

Table 4 provides a breakdown of these operating costs and their contribution to the total production cost. As shown, the potential feedstock credits (the waste tipping fee charged by the HTL plant) have the most significant impact on the operating costs, ranging from $0.58 to $1.93 per GGE. The credits gained depend on the feedstock type and wet waste location. The wet waste avoided disposal cost, estimated according to the results of a wet waste recourses analysis,[43] is detailed in Tables S3 and S4. Additionally, each feedstock is considered to have a transportation cost, as outlined in the SI. Even without feedstock credits, the total operating cost varies in the range of $2.18–$2.99 per GGE across all cases. In the current design, HTL solid was sent to landfill, while NH_3 and COD in aqueous-phase product were removed before disposal. The associated treatment and disposal cost ranges from $0.79 to $1.07 per GGE, accounting for 30–37% of the overall operating cost excluding feedstock credits. This cost can potentially be further reduced by using advanced by-product valorisation technologies,[44] while additional research is required to advance their technology maturity for industrial deployment. It was discovered that food waste HTL demonstrates the lowest operating cost, followed by sludge HTL, with manure HTL exhibiting the highest operating cost. This finding can be attributed to the fact that food waste typically has a moisture content of around 70 wt%, requiring minimal dewatering, and boasts a high biocrude yield with fewer heteroatoms. By contrast, manure HTL presents a higher operating cost due to its high oxygen and nitrogen content, as well as significant heavy metal content in the resulting biocrude. Elevated heteroatoms in biocrude can lead to increased hydrogen consumption and fuel loss during the hydrotreating process, and heavy metal content can notably reduce the catalyst's lifetime. Furthermore, the operating costs for marine fuel scenarios involving sludge, manure, and food waste are approximately $0.57, $0.24, and $0.42 per GGE lower than the operating costs for renewable diesel scenarios for these types of waste, whereas there is no apparent cost difference between renewable diesel and SAF scenarios for any of the feedstocks.

3.4 Minimum fuel selling price

The estimated plant capital and operating costs were used to conduct a discounted cash flow calculation to determine the MFSP that aligns with the economic assumptions outlined in Table S5. For simplicity, the fuel products were considered to be a single-fuel product and the MFSPs were determined and reported on a combined product basis. The MFSP cost was divided into (i) capital charges and taxes (referred to as Capex), (ii) operating costs and co-product credits (referred to as Opex), and (iii) feedstock, as illustrated in Fig. 2. The analysis revealed that MFSPs across the feedstock and finished fuels varied from $2.58 to $3.61 per GGE for scenarios with feedstock credits.

As anticipated, the MFSPs for the same feedstock exhibited a similar trend to the total capital investment across the fuel types, ranked as follows: marine < diesel < SAF. This is attributable to the fact that biocrude upgraded for marine application only needs to undergo mild hydrotreating, without the need for further fractionation or deep HDN. Consequently, the Capex and Opex in these cases are significantly lower than those of diesel and SAF upgrading options. For instance, the MFSP of SHTL_M cases was approximately $0.57 and $0.59 per GGE lower than the MFSPs of SHTL_D and SHTL_SAF cases, respectively. Similar trends were observed for manure HTL and food waste HTL in marine scenarios. A comparison revealed that the MFSPs of SAF scenarios were only around $0.05–$0.08 per GGE higher than those of diesel scenarios, a consequence of the integration of a kerosene deep HDN process into the upgrading plant. This marginal increase primarily stems from the additional capital cost of the HDN reactor. Notably, from the results of the HDN experiments, it was established that a mild temperature of 375 °C is adequate for reducing nitrogen levels to below 2 ppm. Furthermore, because of the negligible fuel loss

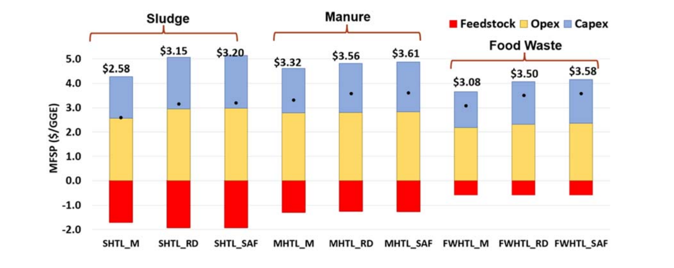

Fig. 2 Summary of MFSP comparison results. Opex = operational expenditure; Capex = capital expenditure; MFSP = minimum fuel selling price; GGE = gasoline gallon equivalent; SHTL = sludge hydrothermal liquefaction; MHTL = manure hydrothermal liquefaction, FWHTL = food waste hydrothermal liquefaction; SAF = sustainable aviation fuel; RD = renewable diesel; M = marine fuel.

(<1%) and minimal hydrogen consumption (0.017–0.020 g per g feed) under these conditions, there is little impact on the MFSP. In comparison to the existing market for marine fuel, RD and SAF, HTL derived biofuel is cost competitive. Specifically, the cost of marine fuel produced from waste sources through HTL ranges from \$2.58 to \$3.32 per GGE, which is similar to the North American average of \$2.10 per GGE over the past two years. The modelled price for HTL-derived RD falls between \$3.15 and \$3.56 per GGE, significantly lower than the average market price for RD, which is \$4.58 per GGE, demonstrating a notable cost advantage. In contrast, the commercial SAF price ranges from \$3.84 to \$9.62 per GGE, indicating that HTL-derived biofuels present a competitive alternative in the market. Comparisons conducted by Huang *et al.*[45] and Li *et al.*[35] also suggest that wet waste HTL pathway is cost competitive with other conversion technologies, such as Fischer–Tropsch, and hydroprocessed esters and fatty acids.

Because the upgrading plant configuration and TEA results were highly similar between renewable diesel application and SAF application in all cases (∼\$0.05 per GGE difference in modeled MFSP), as shown in Fig. 2, the sensitivity study results were expected to be similar. Therefore, sensitivity studies were only conducted for marine and SAF application to investigate the effects of key process variables on the modeled MFSP. The results are shown in Fig. 3. In this work, for the HTL plant, variables with potential uncertainties included the scale and capital cost of the HTL plant, feedstock avoided disposal credits, and the costs associated with HTL solid and aqueous treatment. For the biocrude upgrading plant, the chosen variables were plant scale, finished oil yield, and hydrogen consumption. The HTL capital cost, plant scale, and avoided feedstock credits had the most substantial impacts on the MFSP. HTL, as an emerging technology, is still under development for commercialization and is therefore subject to uncertainties related to capital costs. As shown, if the fixed capital cost of the HTL plant (110 dry tons per day) were to triple, the modeled MFSP would potentially increase by \$2.97 per GGE for SAF application and by \$2.57 per GGE for marine application. Additionally, considering that collecting wet waste at scale with cost-effective transportation is possible in some areas within the United States, an HTL plant scale of 1100 dry tons per day could reduce the MFSP by \$1.41 per GGE for SAF application and by \$1.25 per GGE for marine application. Feedstock credits could potentially be received from WRRE facilities because of the large biosolid disposal cost associated with current practices, such as landfilling or incineration. The sludge disposal cost under current practices at Great Lakes Water Authority is approximately \$300 per dry ton,[46] which could drop biocrude costs by \$1.08 per GGE. Additionally, in this work, the HTL solid by-product was assumed to be sent to a landfill, whereas the HTL aqueous phase was assumed to be discharged at a fee based on a tiered COD level, after the removal of ammonia *via* air stripping. The total HTL solid and aqueous treatment costs constituted approximately 54% of the biocrude cost and could potentially be reduced through the use of solid and aqueous valorization technologies.[44] Implementing different upgrading strategies could reduce the MFSP by \$0.67–\$0.75 per GGE if the costs associated with HTL solid and aqueous treatment were reduced by 70% *via* research improvement. By contrast, as indicated in Fig. 3, the variables associated with upgrading plants have a smaller impact on the finished fuel MFSPs than do the variables associated with HTL plants. In particular, hydrogen consumption has the most negligible impact on the MFSP, which can explain the fact that upgrading costs are similar across feedstocks with different hydrogen consumption requirements. A −10% change or +10% change in finished oil yield could lead to a \$0.27 per GGE increase or \$0.34 per GGE decrease in MFSP, respectively, for SAF applications, with similar trends observed for the other two upgrading strategies. Increasing the upgrading plant scale by a factor of 10 can reduce the MFSP by \$0.40–\$0.47 per GGE. By contrast, reducing the upgrading plant scale by 50% could result in an increase in MFSP by \$0.30–\$0.41 per GGE across different upgrading strategies.

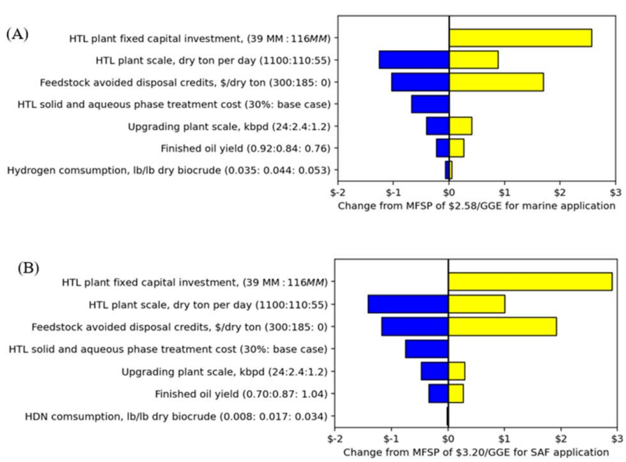

Fig. 3 Sensitivity study of the impact of the key process variables on the MFSP for marine application (A) and SAF application (B). HTL = hydrothermal liquefaction; MFSP = minimum fuel selling price; SAF = sustainable aviation fuel.

3.5 Life cycle emissions

Fig. 4(A) shows the life cycle results of biofuels produced from HTL of wet wastes, measured in grams of CO_2e per megajoule (g CO_2e per MJ) of fuel produced. Overall, the LCA results varied among different feedstocks (*i.e.*, wastewater sludge, swine manure, and food waste), whereas the emissions of different fuels (*i.e.*, marine, renewable diesel, and SAF) produced from the same feedstock were comparable.

The GHG emissions of fuel pathways investigated in this study ranged between −58 and 9 g CO_2e per MJ. There are two main reasons for the small footprint of biofuels produced from wet wastes. First, the biogenic carbon embedded in these feedstocks originates from CO_2 uptake from the atmosphere, which cancels out the biogenic CO_2 emitted during biofuel combustion. Second, GHG emissions from BAU waste management are avoided due to the diversion of wet wastes for fuel production. The avoided emissions are accounted for as GHG credits for the fuel product.

Fuels produced from swine manure and food waste have negative life cycle GHG emissions because of the significant

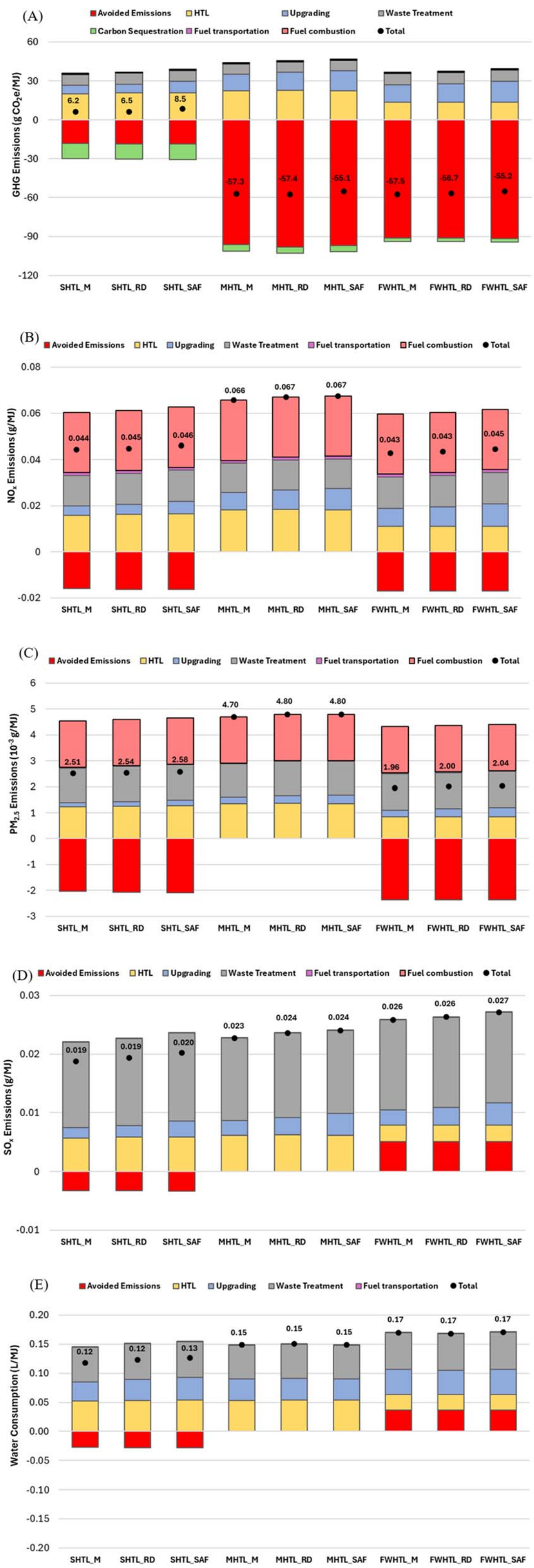

Fig. 4 Comparative life cycle analysis results for (A) GHG emissions, (B) NO_x emissions, (C) $PM_{2.5}$ emissions, (D) SO_x emissions, and (E) water consumption of fuels from wet waste HTL pathways. SHTL = sludge hydrothermal liquefaction; MHTL = manure hydrothermal liquefaction, FWHTL = food waste hydrothermal liquefaction; SAF = sustainable aviation fuel; RD = renewable diesel; M = marine fuel.

GHG credits. This is because BAU management of food waste and swine manure (landfilling of food waste, deep pits and anaerobic lagoons for swine manure management, *etc.*) emits a considerable amount of methane, which is a potent GHG. The avoided methane emissions from BAU management of swine manure and food waste thus translate into significant GHG credits for fuels produced from these feedstocks. On the other hand, sludge is managed *via* anaerobic digestion, and the generated biogas is burned to supply heat on-site while excess biogas is flared. As a result, only a small amount of methane escapes from biogas flaring and leaks during sludge management. Therefore, fuels produced from sludge gain fewer GHG credits than those produced from swine manure or food waste. The food-waste-based pathways have the highest fuel yield during biocrude upgrading, hence the lowest GHG emissions from HTL. On the other hand, the sludge-based pathways consume less natural gas for biocrude upgrading than the other pathways; therefore, sludge has the lowest GHG emissions from biocrude upgrading among the three feedstocks.

Unlike GHG emissions, air pollutants (SO_x, $PM_{2.5}$, and NO_x) are emitted from fuel combustion in considerable quantities. HTL, upgrading, and waste treatment also cause high CAP emissions due to the usage of process fuels and electricity. Swine manure does not carry embedded CAP emission credits from avoided BAU manure management. The BAU of food waste management, on the other hand, involves electricity generation from landfill gas. This practice displaces grid electricity mix and results in a net negative SO_x emission for BAU food waste management. However, when food waste is diverted from BAU to HTL for fuel production, this beneficial SO_x emission reduction is no longer achieved. This foregone benefit is translated into a SO_x penalty for fuels produced from food waste. Therefore, among the three wet wastes investigated in this study, food waste leads to the highest SO_x emissions in its fuel products.

Process water added to make up for the evaporation of cooling water and boiler water is a main contributor to life cycle water consumption. Waste treatment is also a major water consumer because of the water consumption inherent in the production of electricity and chemicals used for treating high-COD wastewater discharge from the HTL facility. As with the case of SO_x emissions, BAU food waste management has net negative water consumption because of power generation from the collected landfill gas displacing the U.S. grid electricity, which is somewhat water intensive;[38,47] such water consumption is foregone and accounted for as a water penalty for the fuel products. As a result, fuels produced from food waste have higher water consumption than those produced from wastewater sludge or swine manure.

The estimated GHG emission from LCA indicates that HTL-derived biofuels could qualify for various federal and state incentive programs, contingent on completing the necessary certifications. Although incentives could further reduce the estimated MFSP (Section 3.4), they were excluded from this baseline TEA to avoid uncertainties arising from their variable pricing and inconsistent program durability over time and location, thus focusing on the technology itself. Overall, RD and SAF pathways may qualify for D3/D5 RIN credits from US EPA's Renewable Fuel Standard (RFS), with a price ranging from \$0.10 to \$3.50 per ethanol gallon equivalent over the past five years, while marine fuel for ocean-going vessels doesn't qualify for RIN credits. 45Z may provide up to $1 per gallon tax credits for RD and marine pathways, and up to $1.25 per gge for SAF pathways with greater than 50% emission reduction and $1.75 per gallon tax credits for SAF pathways with 100% emission reduction. In California, biofuels produced from eligible feedstocks may qualify for low carbon fuel standard (LCFS) credits, which have fluctuated between $75 and $211 per metric ton over the past three years.

4 Conclusions

In this study, detailed process models were developed in Aspen Plus for HTL with different upgrading strategies to produce marine, renewable diesel, and SAF from wet waste. Comprehensive techno-economic comparisons were conducted for nine cases with three types of feedstock (sludge, manure, and food waste) and three biocrude upgrading strategies (marine, renewable diesel, and SAF). The results indicate that different upgrading strategies can efficiently shift the finished fuel share among the targeted fuels without adding much capital or operating costs. Moreover, the TEA results suggest that the MFSPs for all nine HTL cases varied from $2.58 to $3.61 per GGE, with feedstock credits. The estimated MFSPs were close to the market prices of petroleum-based transportation fuels, which demonstrates that the wet waste HTL process has promising economic feasibility and the versatility to shift from the production of one fuel to that of another in response to varying fuel market demands. The LCA results indicate that HTL fuels have lower GHG emissions but comparable or higher CAP emissions and water consumption rates compared with their petroleum-based counterparts and BAU practices. As the industry scales up, these environmental challenges could be addressed through integration and CAP emission mitigation at biorefineries.

Author contributions

Shuyun Li: writing – original draft, methodology, formal analysis. Longwen Ou: writing – original draft, formal analysis. Yuan Jiang: writing – review & editing, methodology, funding acquisition, supervision. Hao Cai: writing – review & editing, supervision. Daniel M. Santosa: writing – review & editing, resources. Uriah J. Kilgore: writing – review & editing. Senthil Subramaniam: writing – review & editing. Igor Kutnyakov: writing – review & editing. Huamin Wang: writing – review & editing, resources. Michael R. Thorson: funding acquisition, supervision. Mariefel Olarte: writing – review & editing, resources.

Conflicts of interest

There are no conflicts to declare.

Abbreviations

BAU	Business as usual
COD	Chemical oxygen demand
FOG	Inedible fats, oils, and grease
FWHTL	Food waste hydrothermal liquefaction
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
GREET	Greenhouse gases, regulated emissions, and energy use in transportation
HDN	Hydrodenitrogenation
HTL	Hydrothermal liquefaction
LCA	Life cycle analysis
MFSP	Minimum fuel selling price
MHTL	Manure hydrothermal liquefaction
RD	Renewable diesel
SAF	Sustainable aviation fuel
SHTL	Sludge hydrothermal liquefaction
TEA	Techno-economic analysis

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5su00647c.

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