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Hydrothermal Liquefaction of Wet Microalgae for Bio-Crude Production: Process Parameters, Catalytic Strategies and Scale-Up Challenges

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Abstract: *Algal biomass is being investigated as a renewable feedstock for liquid fuels because microalgae can grow rapidly, can be cultivated on non-arable land, and can use a range of water sources and carbon dioxide streams. A major barrier in conventional algal biofuel routes is the energy and cost associated with harvesting, dewatering and drying biomass before lipid extraction. Hydrothermal liquefaction (HTL) offers an alternative by converting wet biomass in hot compressed water into a bio-crude product without requiring complete drying. This review synthesises literature reported in the source material on the HTL of wet microalgae, focusing on operating conditions, feedstock composition, catalysts, product separation, aqueous-phase recycling and process integration. Across the studies summarised, reported bio-crude yields commonly fall in the approximate range of 30–70 wt% of dry feed, although values vary with algal strain, reactor configuration, temperature, residence time and product-recovery method. Temperatures around 300–350 °C are frequently reported to favour liquid products, while higher temperatures can increase gas formation and lower temperatures may favour solids. The review also identifies persistent challenges: nitrogen and oxygen in the bio-crude, catalyst cost and deactivation, high-pressure solids handling, uncertain commercial-scale economics, and the need for heat integration. Because the underlying project is literature-based, reported values are presented as results from prior studies rather than new experimental measurements. Further work should prioritise comparable reporting methods, continuous-reactor validation, upgrading performance and integrated techno-economic and environmental assessment.*

Keywords: microalgae; hydrothermal liquefaction; bio-crude; bio-oil; catalyst; aqueous-phase recycling; biorefinery; energy recovery

I. INTRODUCTION

Demand for liquid fuels and concerns about greenhouse-gas emissions have encouraged the development of renewable fuel pathways. Algae are often described as third-generation biofuel feedstocks because they do not necessarily compete with food crops for arable land and may be cultivated in freshwater, brackish water, seawater or wastewater. Their biomass contains lipids, proteins and carbohydrates, and the relative proportions depend on the strain and cultivation conditions [1,2].

Conventional algal biodiesel production generally involves harvesting, dewatering, drying, lipid extraction and conversion of the extracted lipids. These steps can be energy-intensive, and the route mainly utilises the lipid fraction. HTL instead processes wet biomass in pressurised hot water, enabling proteins and carbohydrates as well as lipids to contribute to the product slate [1].

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This article reviews the HTL process and selected developments described in the source literature. It emphasises the links between operating conditions, feedstock characteristics, catalyst selection, product recovery and the challenges that must be addressed before wider deployment.

II. REVIEW APPROACH AND SCOPE

This is a narrative review prepared from the literature and references listed in the supplied mini-project report. It is not a systematic review: no database search protocol, screening flow diagram or independent bibliometric analysis was available in the source material. Numerical values are therefore reported as values cited by the underlying review and individual studies. The source project does not report newly measured experimental data; calculations included here are illustrative only.

III. HTL PROCESS FUNDAMENTALS

In HTL, wet algal slurry is heated under pressure so that water remains a dense reaction medium. Hydrolysis and depolymerisation break down biological macromolecules; subsequent decomposition, dehydration, decarboxylation and deamination produce smaller intermediates. Some intermediates recombine into an oil-like phase, while other material remains in the aqueous phase, forms solid hydrochar or leaves as gas, commonly rich in carbon dioxide [1].

A typical process train comprises wet-algae preparation, slurry mixing, high-pressure pumping, heating and reaction, cooling, gas–liquid–solid separation, bio-crude recovery, and treatment or reuse of the aqueous and solid by-products. Solvent extraction, for example with dichloromethane, is one reported recovery method, but solvent use and recovery affect both measured yield and environmental performance. Filtration and alternative separation approaches should also be evaluated.

IV. EFFECTS OF OPERATING PARAMETERS

4.1 Temperature and pressure

The reviewed sources commonly identify approximately 300–350 °C as a useful temperature range for maximising liquid products. At lower temperatures, incomplete conversion and solid formation may be more prominent; at higher temperatures, secondary reactions and gas formation can reduce the recovered oil fraction [1]. Pressure is required to maintain dense water under reaction conditions. Reported operating ranges vary by reactor and study, so temperature should not be interpreted independently of pressure, residence time and feed composition.

4.2 Residence time and biomass loading

Residence time influences both conversion and secondary degradation. The source report summarises fast-HTL work in which bio-crude yield increased over short reaction times and declined after longer exposure, illustrating that additional reaction time does not always improve oil yield [3]. Slurry solids loading also affects process economics: higher loading reduces the amount of water that must be heated, but the slurry must remain pumpable and the reactor must safely accommodate the feed.

4.3 Feedstock and algal strain

The proportions of lipids, proteins, carbohydrates, ash and cell-wall material vary between algal species and cultivation conditions. This variation changes bio-crude yield and its nitrogen and oxygen content. Studies cited in the source report include Nannochloropsis, Chlorella and Spirulina species, among others. Yield comparisons across different studies should be treated cautiously because the reactors, operating conditions, feedstock composition and product-recovery methods may not be equivalent [1].

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V. CATALYSTS AND PROCESS INTENSIFICATION

Catalysts have been investigated to improve conversion, alter product distribution and reduce heteroatom content. The reviewed studies include alkali compounds, metal oxides, supported transition metals and zeolites. Reported outcomes are feedstock-dependent: a catalyst that improves yield or quality for one strain may provide little benefit for another. Catalyst cost, deactivation, recovery and possible contamination of product streams remain important practical considerations [1,4,5].

Other approaches described in the source literature include aqueous-phase recycling, sequential or two-stage HTL, integration with dark fermentation, continuous processing and co-liquefaction. Aqueous-phase recycling may return nutrients and soluble compounds to the process, although repeated recycling can also lead to accumulation of unwanted compounds. Sequential processing has been reported to reduce hydrochar formation and energy use per unit of oil in selected systems, but these results require validation under comparable conditions [1,6–10].

VI. PRODUCT RECOVERY, UPGRADING AND CO-PRODUCTS

The HTL product mixture generally contains bio-crude, an aqueous phase, hydrochar and gas. Recovery method influences the amount and composition of bio-crude measured. Solvent extraction can recover oil-like compounds but requires solvent handling and recovery; alternative separation approaches may change the heteroatom content of the recovered product. Studies should report the extraction solvent, solvent-to-feed ratio, recovery procedure and mass-balance closure so that yields can be compared meaningfully.

Algal bio-crude can contain substantial nitrogen and oxygen because proteins and oxygenated biomolecules contribute to the feed. These heteroatoms, together with acidity and viscosity, can limit direct use as a transport fuel. Hydrotreatment or hydrodeoxygenation may improve fuel properties, but adds hydrogen demand, catalyst requirements and cost. The aqueous phase may contain nutrients and dissolved organics and may be treated, recycled or used for nutrient recovery. Hydrochar may be assessed for suitable material or soil-related applications only after its composition and contaminant profile are established. A carbon-dioxide-rich gas stream may be considered for reuse in cultivation where feasible [1].

VII. LITERATURE RESULTS AND COMPARISON

The following examples are transcribed from the supplied project report's summary of published work. They are not new experimental results and should be checked against the original papers before submission.

These examples indicate that both feedstock and process configuration affect performance. However, they do not establish a single universally optimal catalyst or operating condition. A robust comparison requires a common basis for dry-feed mass, product recovery, heating value, energy consumption and mass-balance closure.

VIII. RESEARCH GAPS AND SCALE-UP CHALLENGES

Several gaps emerge from the reviewed material. First, many studies are laboratory-scale, while commercial-scale data on cost, reliability and environmental performance remain limited. Second, high nitrogen and oxygen contents create an upgrading requirement that affects hydrogen consumption, catalyst life and product value. Third, catalyst deactivation and recovery must be evaluated alongside initial yield. Fourth, continuous operation presents challenges in pumping solids-containing slurries, maintaining heat transfer, controlling pressure and separating products. Finally, the energy needed to heat water can approach the energy contained in the recovered oil in low-solids systems, making heat recovery and suitable biomass loading central to process design [1].

Future studies should report complete mass and energy balances, characterise feedstock composition, use replicate runs with uncertainty estimates, and compare products using consistent analytical methods. Pilot-scale continuous operation and transparent techno-economic and life-cycle assessments are needed to determine whether environmental benefits persist when cultivation, harvesting, pumping, heating, solvent recovery and upgrading are included.

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IX. ENVIRONMENTAL AND PROCESS-SAFETY CONSIDERATIONS

Potential sustainability benefits include the use of non-arable land, wastewater nutrients, carbon dioxide streams and wet biomass. These benefits depend on local conditions and should not be assumed without a system-level assessment. Wastewater-derived biomass and hydrochar require contaminant testing before reuse. HTL also involves high temperature and pressure, and solvent extraction may involve hazardous volatile solvents. Any experimental work must use appropriately rated equipment, documented risk assessment, trained supervision, suitable pressure-relief systems and approved solvent-handling procedures.

X. CONCLUSIONS

Hydrothermal liquefaction is a promising route for converting wet microalgae into bio-crude while avoiding the complete drying required by many conventional lipid-based routes. The literature summarised in the source report indicates that temperature, residence time, biomass loading, algal composition, catalysts and separation methods all influence product yield and quality. Reported yields span a broad range and should not be treated as directly comparable without accounting for differences in experimental conditions.

The main barriers to wider application are bio-crude upgrading, energy integration, catalyst performance, continuous high-pressure operation, product separation and commercial-scale economics. The most useful next steps are well-documented experiments or pilot studies with complete mass and energy balances, followed by techno-economic and environmental assessment. This manuscript is a narrative review based on the supplied project report and should be strengthened through verification of every reference, expansion of the literature search and adaptation to the chosen journal's author guidelines before submission.

Author contributions

To be completed by the authors. Specify each author's actual contribution to conceptualisation, literature review, writing, revision and approval.

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Conflicts of interest

The authors should declare any actual conflicts of interest or state that none exist, if accurate.

Data availability

No new experimental dataset was generated for this narrative review. Any supplementary extraction table prepared for submission should be made available as required by the selected journal.

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