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Decarbonizing Marine Supply Chains through AI Optimized HTL of Macroalgae: A Renewable Port Energy Solution

Ramaiah Thirumalaikumar[1,*], Fatma Al-Jabri[1], Jaikumar Vasudevan[2], Faizal Al-Marzuqi[3], Hawa Al-Ghassani[1], Riama Al Masruri[1]

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ABSTRACT

The current work examines the use of AI to optimize hydrothermal liquefaction (HTL) of marine macroalgae for sustainable biofuel production, supports the decarbonization and carbon-neutral supply chain target. The research investigation shows the ultimate bio-oil yield of 23.5% at 280 °C, 30 minutes, and 15% solid loading, closely matching AI predictions with less than 2% error. The produced biochar contains 55% carbon, making it valuable for soil enhancement and carbon sequestration. AI investigation based on the studies highlights the reduction in global warming potential of CO_2 per tons of the product investigated for corn, wood and Algae. This demonstrates the potential of algae biofuel to drastically lower the carbon footprint of maritime logistics. Integrating algae-derived biofuel with wave and tidal energy can share the 25% of renewable power for green port operations. Addition of investigation with existed approach supports resilient, low-carbon supply chains. This research gives the way for greener, more efficient maritime industries.

1. Introduction.

Ocean acidification has grown due to rising atmospheric carbon dioxide (CO_2) concentrations, exposing marine environments and the steadiness of the global climate. In order to diminish the greenhouse gas (GHG) emissions, lowering the carbon footprint for port operations, and step up the sustainable maritime transportation, decarbonizing marine supply chains has become essential. Green port operations and low-carbon shipping are promising outcomes of renewable energy systems based on marine biomass. There are many technologies that provide the solution; even though, Hydrothermal liquefaction (HTL) of macroalgae is one of these methods that provides a green solution to produce renewable biofuels without competing with first-generation and second - generation resources (Djandja et al., 2020; Duan et al., 2013; Durak and Genel, 2020).

Marine macroalgae is potential for carbon capture, faster growth rate, and compatibility with moisture biomass conversion processes make it an attractive renewable feedstock for sustainable port energy systems (Lutzu and Dunford, 2019; Milledge et al., 2019). HTL enhances the efficiency of the process and minimizes the energy consumption by directly converting wet biomass into bio-crude without the need for energy-

[1]Process Engineering Department, National University of Science and Technology – International Maritime College Oman, Sultanate of Oman. E-mail Address: thirumalai@imco.edu.om.

[2]Chemical Engineering Department, Sri Sivasubramaniya Nadar College of Engineering, Kalavakkam, Chennai, Tamil Nadu, India. E-mail Address: jaikumarv@ssn.edu.in.

[3]Supportive Requirements Department, University of Technology and Applied Sciences, Sohar, Sultanate of Oman.

[*]Corresponding authors: Ramaiah Thirumalaikumar, E-mail Address: thirumalai@imco.edu.om; Jaikumar Vasudevan, E-mail Address: jaikumarv@ssn.edu.in.

intensive drying stages, in contrast to traditional thermochemical conversion techniques. Additionally, HTL produces useful byproducts like biochar, which can support circular resource management via applications like environmental remediation and wastewater treatment (Elliott et al., 2015; Niska et al., n.d.).

The leading application of HTL produced biochar is as an adsorbent to remove impurities from wastewater. Biochar can efficiently remove heavy metals and organic pollutants from wastewater due to its surface-active fractions. The previously published work highlights the significance of looking into the cost - effective utilization of HTL by-products, particularly biochar and aqueous phase, to recover biofertilizers from wet organic solid waste (Ighalo et al., 2025; Jeon et al., 2013).

To increase the production of bio-oil from the biomass, the catalyst performance in the hydrothermal liquefaction of macroalgae is critical. The components of the bio-oil made from macroalgae can interact with catalysts in hydrothermal liquefaction processes, influencing their stability, selectivity, and catalytic activity (Gollakota et al., 2018; Li et al., 2026; Q. Zhang and Cai, 2008). When producing bio-oil from macroalgae, the employment of catalysts in hydrothermal liquefaction processes has several benefits. Initially, the breakdown of complex organic molecules found in macroalgae into simpler, more useful components is greatly aided by catalysts (Q. Zhang and Cai, 2008; Zhou and Dunford, 2017).

Based on studies, Marine Macro Algae and Chicken waste mixture used with sodium hydroxide impact on the maximum bio-oil yield of 23.3 wt% for the optimum working condition such as 280 °C. However, optimizing HTL operating conditions remains challenging due to the complex interactions between temperature, reaction time, and biomass characteristics. In recent work, the Aspen HYSYS simulation studies provide the maximum of side cut enhancement predictions using simulation and it has great agreement with the experimental work (Thirumalaikumar and Jaikumar, 2024). Majority of the pretreatment methods include low concentrated alkali, low concentrated acid pretreatment. The above treated methods require development due to their obstacles such as extraordinary thermal conditions and rigorous chemicals for efficient elimination of lignin materials. The sonicated method is a promising pretreatment method to generate the necessary elements of fragments and reactive constituents for advanced transformation and greater bio-oil yield (Ramaiya and Vasudevan, 2024).

By estimating ideal HTL conditions, increasing bio-crude production, boosting energy efficiency, and facilitating the incorporation of fuels derived from macroalgae into marine energy systems, artificial intelligence (AI)-based optimization techniques can overcome these constraints. This approach aligns with Oman Vision 2040 by promoting clean energy innovation, economic diversification, and sustainable industrial development (Saini et al., 2024; Schwede et al., 2013; Toor et al., 2011).

There are many benefits in practical terms; key significance is that, when compared to standard harvests, algae is produced easily by water and marine environments and on soils that are not suited. There is a need for arable land to be eliminated by using sewage water to promote the growth of algae while suppressing other crops. Algae may grow in marine water and require less carbon dioxide, light, and water than traditional crops (Gandhi et al., 2013; Guo et al., 2015; W. Zhang et al., 2015). This research work is mainly focused on catalyst influence on the bio-oil yield using hydrothermal liquefaction using Marine Macro Algae (*Ulva* species) with chicken waste.

2. Methodology.

2.1. Preparation of the Catalyst.

The catalyst, g-C_3N_4, was prepared using melamine powder ordered from Sigma Aldrich. The synthesis process consists of the addition of heat in melamine powder (1.5 gm) in a partially closed system by a muffle furnace. The thermal rose to 550 °C by the degree of 25 °C per min in nitrogen stream in 20 minutes. Subsequently, thermal oxidation and etching were conducted at 540 °C in the absence of nitrogen for durations ranging from 3 to 12 hours with three-hour increments per time step. After undergoing the cooling process, the resulting product was collected for subsequent analysis, which involved characterizing and conducting hydrothermal liquefaction experiments (Al Marzouqi et al., 2019).

2.2. Experimental Procedure.

Figure 1 represents the experimental setup of the Hydrothermal reactor with the Arm field cooler along with the temperature and pressure controller. The Hydrothermal Reactor with the capacity of 500 ml by ZZKD Keda Machinery, China. Fresh Marine Macro algal biomass was gathered and carefully cleaned to remove the undesirable elements, sand, and dirt. The washed fresh algae was washed at room temperature using ultrasound at 65% of its maximum power for about six minutes. This stage improved the reactor's future conversion efficiency by dissolving the algal structure. To increase uniformity and decrease particle size, the algae were treated with ultrasound (Figure 2). The experiment was carried out for the various algal masses and working temperature of 285 °C with pressure of 22 MPa for the various catalyst loads (0.2, 0.4, 0.6, 0.8, and 1 g) and three different retention times (10, 20, and 80 mins) (Ramaiya et al., 2024).

3. Results and Discussion.

3.1. Bio Oil Yield for the Catalyst Dose with Retention Time.

Figures 3, 4 and 5 indicate the effect of catalyst g-C_3N_4 dosage on marine macroalgae with water mixture. The mesoporous nature was investigated by surface morphology. The bio-oil yield increased with the addition of g-C_3N_4 loads at the different mixing times (10, 20, and 80 mins). It clearly shows a higher yield for the lower catalyst dosage; further addition shows a declining trend. At the minimum amount of catalyst dose (0 to 0.2–0.3 g), there is greater yield because of the available active sites on the catalyst side. When increasing the retention time from 10, 20 to 80 minutes, higher yield and cross kinetics were produced, such as breaking starts to control. This

Figure 1: Setup for Hydrothermal Reactor [18].

Source: Authors.

directs to a marginally elevated peak yield as retention time increases, since the supplied raw treated Macro Algae have duration to interact with the g-C_3N_4.

The maximum yield at 0.3 g in Figure 3 clearly indicates the standard catalyst load where bio-oil yield is increased. Though, the yield drops when the catalyst load rises over 0.3 g, reaching 11% at 2.0 g. This decline is due to the effects of overloading the catalyst, which can initiate clustering, a decrease in surface area, and limits on mass transfer, all of which lower the catalyst efficiency (Qu et al., 2024; van Hal et al., 2014; Yakovleva et al., 2016).

Figure 4 shows the bio-oil yield percent with graphene carbon tetranitride dosage. The yield gradually increases from 5% to the maximum amount of 16.5% for the catalyst dose nil to 0.3 g, showing that the catalytic activity improves the reaction efficiency by supplying active reaction sites to convert raw marine algae into bio-oil. The greater yield achieved at 0.3 g suggests this is the optimal catalyst loading at this reaction time of 20 mins. Further addition of catalyst dosage causes the bio-oil yield to start reducing, to 12% at 1.0 g. The above result has closer agreement with past studies (Ma et al., 2020; Qu et al., 2024).

Even though, above the suitable dose (0.3 g), the quantity of bio-oil decreases regardless of retention time. The composition and properties of the bio-oil in the hydrothermal liquefaction process were influenced by various catalysts. Different catalysts demonstrated varying effectiveness in promoting desired reactions, leading to maximum yields and improved quality of bio-oil compared to others. Additionally, factors such as catalyst dosage and solid-to-liquid ratio played a key role in determining both the output and composition of bio-oil. It was observed that changes in temperature and composition also impacted the performance of catalysts during *Ulva* macroalgae liquefaction (Qu et al., 2024; Venkatachalam et al., 2023).

Figure 2: Ultrasonication of macro algae.

Source: Authors.

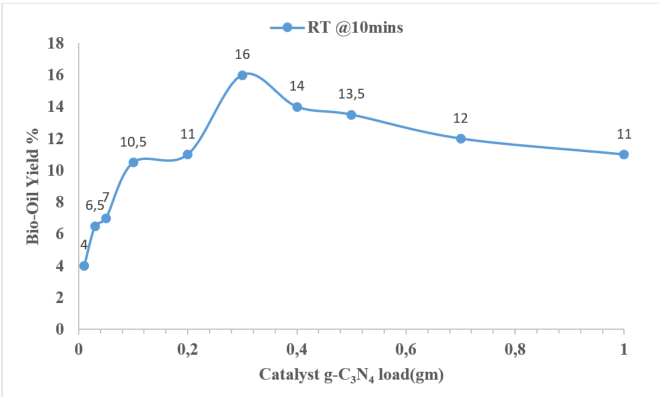
3.2. AI Optimization Based on Different Methods.

The higher bio-crude yield gives clear renewable energy production per kilogram of marine biomass, improving fuel availability for ports and maritime logistics. When integrated with renewable port energy systems, AI-optimized HTL reduces reliance on fossil diesel and lowers life cycle emissions. The comparison presented in Figure 6 clearly indicates the bio-oil yield based on the fact that AI optimization is not incremental but structurally transformative for the environment; it enables scalable biofuel production for low-carbon shipping and green port operations (Thirumalaikumar and Jaikumar, 2024; Vadlamudi et al., 2024).

3.3. Global Warming Potential for Different Feedstock for Renewable Port.

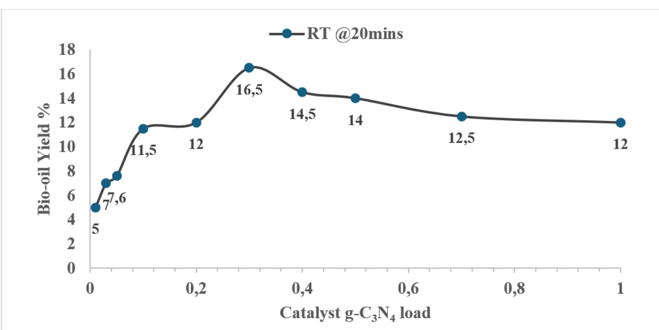
Figure 7 shows the global warming potential based on bio-oil and biochar performance for the suitable port solution, because the global warming potential for the mass of the CO_2 per ton of the product investigated for the corn stove and wood chip biomass and marine algae is suitable. In this AI prediction, algae-produced biochar provides the minimal amount of global warming potential when compared to wood and corn biomass. It gives a clear understanding about renewable port energy solutions when the bio-oil is blended with fossil fuel. It has a greater impact on environmental balance solutions (Hirani et al., 2018).

Figure 3: g-C_3N_4 effect on bio-oil yield at the retention time of 10 min.



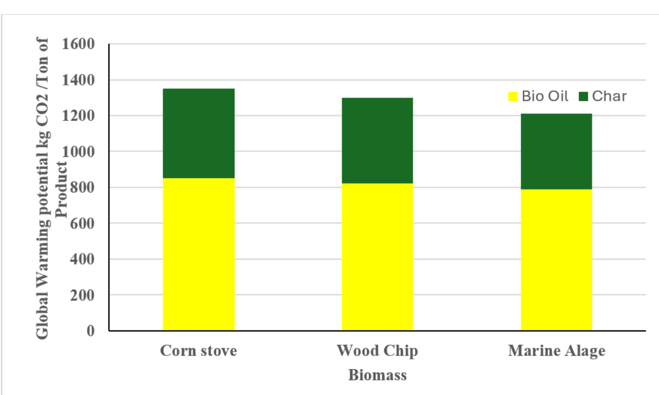
Source: Authors.

Figure 4: g-C_3N_4 effect on bio-oil yield at the retention time of 20 min.



Source: Authors.

Figure 7: Global warming potential for various biomass.

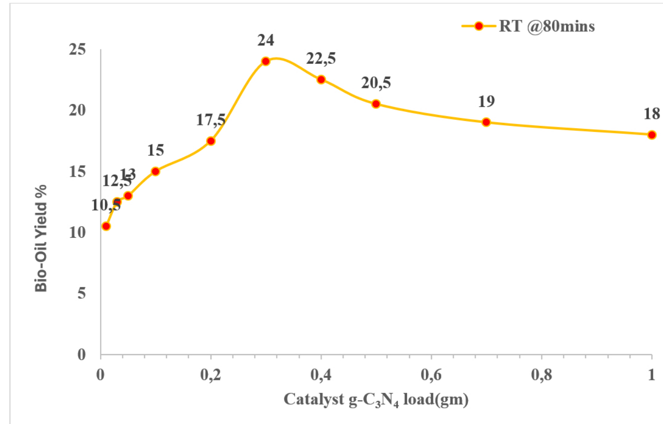


Source: Authors.

Conclusions.

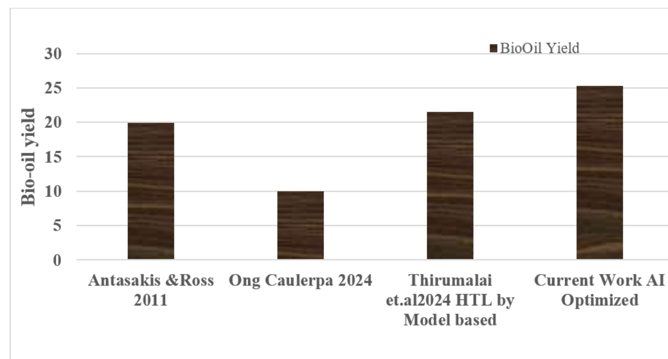
The optimum values for the bio-oil production using hydrothermal liquefaction process are 280 °C and a pressure of 18 MPa and 15% solid-liquid ratio, with the 80 min retention time and 0.3 gm catalyst loading. The sonicated macroalgae mixture was 2.5 times higher than the pure algae with water. The maximum bio-oil yield was at 0.3 gm graphite carbon tetranitride with 80 min retention time, based on the performed experiment (10 min, 20 min, and 80 min). It has good agreement with previous studies. The global warming potential for the different feedstocks for algae CO_2 potential per ton of product is predicted using artificial intelligence. It demonstrates that the renewable port solution for marine machinery performs better. It enhances the eco-friendly solution to the marine environment.

Figure 5: g-C_3N_4 effect on bio-oil yield at the retention time of 80 min.



Source: Authors.

Figure 6: Comparison of bio-oil yield using AI optimization.



Source: Authors.

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Conflicts of Interest.

The authors declare that there are no conflicts of interest.

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