EUGLENA MARINE BIOFUEL: INNOVATING SUSTAINABLE LOW CARBON ENERGY FOR THE FUTURE OF SHIPPING

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Abstract. *The maritime sector accounts for nearly 3% of global greenhouse gas (GHG) emissions and is under increasing pressure to decarbonize. This paper presents a concept for an integrated port–ship biofuel supply chain utilizing Euglena gracilis wax ester co-processed with waste cooking oil (WCO), drawing on advancements by Euglena Co., Ltd in Japan. The proposed pathway integrates large-scale hybrid raceway fermenter cultivation, energy-efficient wet extraction using liquid dimethyl ether (DME), catalytic upgrading to drop-in green diesel/HEFA, and valorization of co-products. The inclusion of WCO expands lipid feedstock diversity, supports circular economy objectives, and lowers production costs. Literature-based techno-economic analysis (TEA) and life cycle assessment (LCA) indicate strong potential for producing renewable marine fuels that comply with international shipping fuel regulations. A phased R&D roadmap is outlined, featuring pilot trials on harbor tugboats integrated with renewable energy and CO_2 capture, aligning with Indonesia's Asta Cita Point 5 on downstream industrialization and Point 2 on green economy and advancing SDG 7 and SDG 13 through a sustainable maritime biofuel value chain.*

Keywords: *circular economy, euglena gracilis, maritime biofuel, waste cooking oil*

INTRODUCTION

International shipping contributes approximately 2–3% of global anthropogenic CO_2 emissions and faces growing regulatory pressure as the International Maritime Organization (IMO) tightens its GHG reduction strategy, while international bodies such as the EU and UNCTAD emphasize pathways toward net zero by mid-century (IEA Bioenergy, 2023). Achieving deep decarbonization in this sector requires scalable, low-carbon, drop-in fuels that can complement energy-efficiency measures and emerging alternatives such as hydrogen and ammonia. Among these, biofuels with low life cycle GHG intensity particularly algal biofuel routes co-integrated with waste CO_2 and renewable electricity are emerging as a promising pathway for maritime applications (NREL, 2022).

One organism of particular interest is Euglena gracilis, which aerobically accumulates the β-1,3-glucan polysaccharide paramylon and, under anaerobic conditions, converts this carbon reserve into long-chain wax esters suitable for catalytic upgrading into diesel and jet fuel (Ogbonna et al., 2021). Laboratory studies have demonstrated competitive wax ester yields with optimized cultivation and fermentation, while co-products such as paramylon and proteins unique to Euglena offer additional revenue streams to improve process economics (Inui et al., 2017). Advanced imaging techniques such as Raman microspectroscopy have visualized wax ester formation at the single-cell level, providing insights for strain selection and process optimization (Ikehara et al., 2020).

Japan's Euglena Co., Ltd. has demonstrated the commercial feasibility of this approach through the development of EMBIO (Euglena Marine Biofuel), a drop-in fuel blend derived from Euglena biomass and waste cooking oil (WCO), also known as used cooking oil (UCO) (Euglena Co., Ltd., 2020). Integrating WCO as a co-feedstock increases fuel yield, reduces upstream cultivation costs, and valorizes urban waste streams, thus addressing both CO_2 emissions and waste oil disposal challenges simultaneously (Matsumoto et al., 2018).

Despite successful laboratory and pilot trials including energy-efficient wet extraction using liquid dimethyl ether (DME) and limited sea trials there remains a notable gap in the development of a port-scale integrated supply chain that links large-scale Euglena cultivation (co-located with industrial CO_2 sources), DME- based extraction, catalytic upgrading to drop-in green diesel/HEFA, and blending with WCO, supported by comprehensive techno-economic analysis (TEA) and life- cycle assessment (LCA) tailored to maritime operations such as tugboats and short- sea vessels (NREL, 2022).

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This study addresses that gap by synthesizing current literature, identifying technical and economic bottlenecks, and proposing a phased R&D and pilot implementation roadmap. The proposed concept directly supports Indonesia's Asta Cita particularly Point 5 on downstream industrialization and Point 2 on green economy and aligns with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by advancing a sustainable maritime biofuel value chain capable of contributing to mid-century net-zero targets.

This study aims to optimize the utilization of *Euglena gracilis* through co-processing with waste cooking oil (WCO) to produce cost-effective, low-carbon drop-in marine biofuel, while identifying key technological and economic bottlenecks in developing a port-scale integrated supply chain. It proposes an integrated biofuel supply model based on wax ester production and evaluates its technical, economic, and environmental performance using Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA). Furthermore, the study develops an R&D and pilot-scale roadmap for maritime applications such as tugboats and short-sea vessels. The implementation of this pathway is expected to support Indonesia's Asta Cita agenda, particularly in industrial downstreaming and green economy development, contribute to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) through reduced maritime greenhouse gas emissions, and promote circular economy principles by valorizing waste CO_2 and WCO as renewable energy feedstocks.

METHODOLOGY

This research employs a mixed-method approach combining conceptual framework development, computational modelling, and literature synthesis, complemented by a proposed laboratory-to-pilot experimental validation plan. The methodology is structured into four main stages, ensuring that the outputs directly inform both the technical feasibility and strategic alignment with Indonesia's maritime decarbonization objectives.

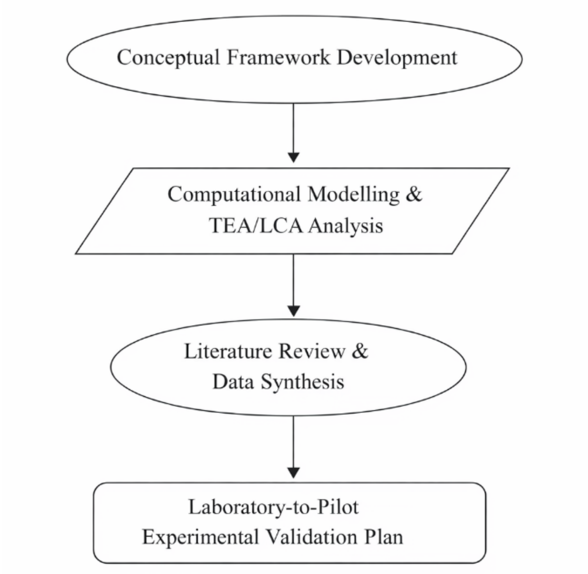

Figure 1. Flowchart Methodology

Systematic Literature Review

A targeted and systematic literature review was conducted to establish a robust knowledge base across five thematic areas:

1. Euglena gracilis Wax Ester Biosynthesis and Cultivation covering photoautotrophic, mixotrophic, and heterotrophic growth strategies, with an emphasis on nitrogen management for lipid induction (Watanabe et al., 2018)
2. Energy-Efficient Wet Extraction Methods with a focus on liquid dimethyl ether (DME) as a low-energy, recyclable, and environmentally benign solvent (Ota et al., 2019).
3. Catalytic Upgrading Pathways particularly hydroprocessed esters and fatty acids (HEFA) for producing low-sulfur green diesel suitable for marine fuel standards (IEA Bioenergy, 2023).

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4. Marine Fuel Compatibility & Sea Trial Data including blending with used cooking oil (UCO) and referencing the MOL Euglena demonstrations (Euglena Co., 2022)
5. Techno-Economic Analysis (TEA) and Life-Cycle Assessment (LCA) leveraging recent harmonized modelling studies for microalgal biofuels (Davis et al., 2020).

Sources were collected from PubMed, ScienceDirect, Scopus, Energy.gov, IMO publications, and corporate press releases. Key experimental reports and meta- analyses were synthesized to inform the conceptual process design, modelling assumptions, and scalability considerations.

Proposed Laboratory-Scale Experimental Plan

To enable translation from conceptual modelling to pilot-scale readiness, a comparative laboratory trial is proposed:

1. Strain Selection Comparative screening of a locally adapted E. gracilis isolate (815) versus an industrial benchmark strain (Euglena Z) under three regimes: photoautotrophic, mixotrophic, and heterotrophic (Ogbonna et al., 2018)
2. Cultivation Strategy A hybrid approach, open raceway ponds for bulk biomass under semicontinuous nutrient management, followed by nitrogen-starvation and fermenter-assisted anaerobic induction to maximize wax ester accumulation. Productivity scenarios modelled include a conservative baseline (~11 $g \cdot m^{-2} \cdot day^{-1}$) and an optimistic range (30–40 $g \cdot m^{-2} \cdot day^{-1}$) (Chisti, 2017).
3. Harvesting & Extraction Bench-scale DME wet extraction (solvent:biomass ratio 8:1, 5 min agitation) following Ota (Ota et al., 2019), scaled to a continuous plug-flow DME extractor concept. Extract composition will be analysed by GC-MS and GC-FID, with residual biomass characterized for co-product recovery (paramylon, protein).
4. Upgrading & Blending Catalytic hydrodeoxygenation/hydrotreating (HEFA route) to produce low-sulfur green diesel, blended with UCO at 10–30% v/v to match fuel characteristics used in MOL Euglena trials (MOL, 2019). Final fuels will undergo ISO 8217 compliance testing and bench-scale engine trials in small marine diesel units.

Techno-Economic Analysis (TEA) and Life-Cycle Assessment (LCA)

An nth-plant TEA and cradle-to-grave LCA will be developed following NREL/BETO harmonized modelling guidelines (Davis et al., 2020). Key parameters include:

- Biomass productivity and wax ester fraction
- Extraction efficiency and DME solvent recovery
- Electricity grid carbon intensity
- CO_2 feedstock source (industrial flue gas vs direct air capture)
- Co-product credits (paramylon, protein)
- UCO blending ratios

Sensitivity and scenario analyses will determine economic break-even points and CO_2 abatement costs, aligned with maritime decarbonization targets (GREET Model, 2024).

Pilot & Demonstration Plan

A port-integrated pilot demonstration is proposed at a medium-sized Indonesian harbor:

1. Cultivation Facility co located with an industrial CO_2 emitter (e.g., cement or power plant) to ensure cost effective and sustainable carbon sourcing.
2. DME Extraction Unit positioned adjacent to cultivation ponds to minimize biomass transport costs and degradation losses.
3. Upgrading & Blending crude wax ester upgraded via mobile hydrotreating skid or off-site refinery co processing, followed by on site UCO blending.
4. Bunkering Trial pilot-scale bunkering using port tugboats, mirroring MOL Euglena operational protocols (Euglena Co., 2022).

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The pilot will generate real world performance, fuel quality, and emissions data to validate TEA and LCA outcomes, refine supply chain modelling, and support commercial scale-up strategies for the Euglena UCO maritime biofuel pathway.

Euglena Biology and Wax-Ester Fermentation

Euglena gracilis is a unique unicellular microalga that stores carbohydrate in the form of paramylon (β-1,3-glucan) and can biochemically convert it into long- chain wax esters under hypoxic or anaerobic conditions through a process known as wax-ester fermentation (Inui et al., 2019). The resulting wax esters typically contain C10–C18 fatty acids and alcohols (e.g., myristic acid/myristyl alcohol), making them suitable as feedstock for catalytic upgrading to diesel and jet fuel fractions (Watanabe., 2018). Wax ester content varies significantly by strain and cultivation conditions: while typical heterotrophic cultures yield ~20–25% dry weight lipids, optimized strains and cultivation regimes have reported exceptionally high wax ester fractions up to ~60–70% (Kato et al., 2017). This variability presents both an opportunity for strain improvement and a challenge for consistent scale-up.

Used Cooking Oil (UCO) Waste as a Biofuel Feedstock in Indonesia

In parallel with Euglena-based biofuels, used cooking oil (UCO) represents a significant underutilized renewable feedstock in Indonesia. The country generates an estimated 3–4 million liters of UCO per month in urban areas (Arifin et al., 2018), much of which is improperly disposed into waterways, causing environmental pollution and public health risks. UCO can be converted into biodiesel through transesterification, producing a fuel compatible with B20–B30 blending programs (BPPT, 2020). Although UCO collection faces logistical and quality challenges, synergies could be explored where UCO is co-processed or blended with Euglena-derived esters, potentially lowering production costs and improving the renewable fuel supply for the marine sector. The integration of microalgae and waste oil valorization aligns with Indonesia’s renewable energy targets and circular economy strategies.

Cultivation Modes, Productivity, and Co-Products

Euglena can grow under phototrophic, mixotrophic, or heterotrophic modes, with nutrient limitation (particularly nitrogen starvation) and carbon supplementation (ethanol, glucose) shifting metabolic allocation toward either paramylon or lipid accumulation (Ogawa et al., 2015). Areal productivities in semicontinuous open raceway systems under nitrogen-managed conditions have been reported at ~8–11 $g\ m^{-2}\ d^{-1}$ (Chisti, 2017), while laboratory and photobioreactor trials under optimal conditions have reached much higher theoretical yields. However, maintaining consistently high productivity at industrial scales remains a major challenge. Co products such as paramylon, proteins, and pigments (e.g., β-carotene) offer additional revenue streams that can enhance techno-economic viability (Sugiyama, 2021).

Wet Extraction Using Liquefied Dimethyl Ether (DME)

Liquefied dimethyl ether (DME) has emerged as an energy efficient, food- compatible solvent capable of directly extracting lipids from wet microalgal biomass without prior drying. Bench-scale studies with Euglena have demonstrated near-quantitative oil recovery (up to 96.7%) using mild operational conditions (solvent:biomass ratio 8:1 wet basis, 5 min shaking, low-pressure operation) (Yamada, 2016). DME penetrates wet cells effectively, and upon depressurization, it evaporates, allowing simple separation of the extracted oil. This method avoids the high energy cost of thermal drying and reduces the need for harsh mechanical cell disruption. Nevertheless, industrial implementation requires robust safety measures, efficient solvent recovery systems, and downstream refining to remove residual heteroatoms before upgrading (Sander et al., 2020).

Upgrading Wax Esters To Marine-Compatible Fuels

Wax esters derived from Euglena can be hydrodeoxygenated and cracked catalytically to yield hydrocarbon fractions resembling diesel and jet fuels (Hirata et al., 2015). The resulting biofuels require characterization of fuel properties such as cetane number, viscosity, cold flow, and sulfur content against ISO 8217 standards for marine fuels. Small scale trials have been conducted, including the Mitsui O.S.K. Lines

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(MOL) tugboat test using Euglena based renewable biodiesel, demonstrating operational feasibility for auxiliary engines and short route ferries (MOL, 2019). These findings indicate potential for partial replacement of marine gas oil in domestic shipping.

Techno-Economic Analysis (TEA) & Life Cycle Assessment (LCA) of Microalgal Biofuels

Recent TEA and LCA studies suggest that microalgal biofuels can achieve substantial greenhouse gas (GHG) reductions when coupled with low carbon electricity, CO_2 capture from industrial point sources, and co product valorization (Davis et al., 2020). However, conventional algal fuel pathways often face higher energy use and GHG emissions compared to fossil diesel when relying on carbon- intensive electricity grids or energy-heavy drying steps (Batan et al., 2020). Integration of waste CO_2, wastewater nutrient recycling, DME based wet extraction, and high value co products can narrow the cost and emissions gap, making large-scale deployment more feasible.

RESULTS AND DISCUSSION

Main Findings from Literature

Euglena derived biodiesel, particularly in the form of *EMBIO* (*Euglena Marine Biofuel)*, is fully compatible with diesel engines used in vehicles and marine vessels, including small tugboats and auxiliary ships. Since EMBIO is a drop-in fuel, it can utilize existing refueling infrastructure without modifications to engines or vessels, facilitating practical deployment and rapid adoption (Euglena Co., 2020).

DME based wet extraction provides rapid and highly efficient oil recovery (~96.7% under bench-scale conditions: 8:1 solvent-to-biomass ratio, 5 min shaking for E. gracilis), eliminating the need for energy-intensive drying and reducing downstream processing energy requirements. Nonetheless, industrial-scale implementation requires careful DME safety design and solvent recycling schemes to ensure operational reliability (Yamada, 2016).

Sea trials using Euglena-derived biodiesel, such as the MOL tugboat demonstration, have confirmed practical operability for small vessels, indicating potential scalability to port-based operations or small fleet applications (MOL, 2019). Literature-based TEA and LCA studies consistently highlight that substantial GHG reductions are achievable when cultivation and processing utilize low-carbon electricity, CO_2 from industrial or waste sources, and co-product valorization. Integrating local renewable energy, wastewater nutrients, and urban CO_2 streams maximizes environmental benefits while improving economic feasibility (DOE, 2023).

The Manufacturing Process of EMBIO (Euglena Marine Biofuel)

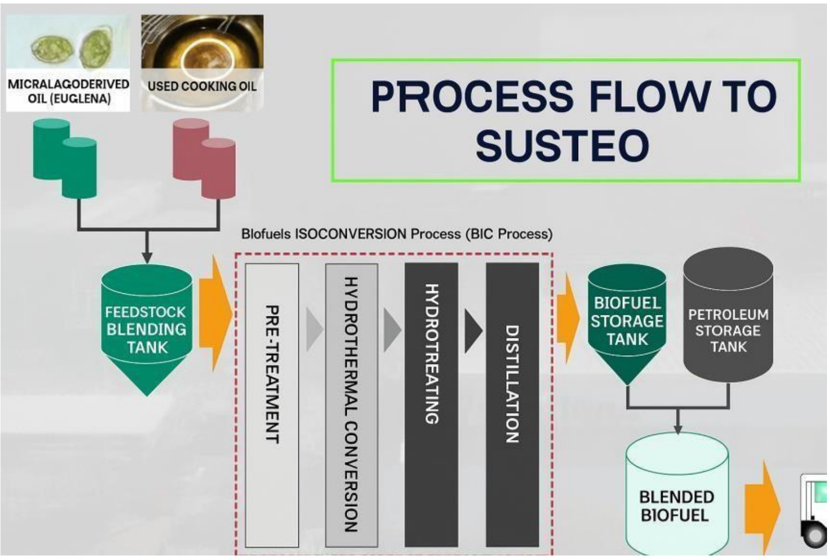

Figure 2. Manufacturing Process Flowchart of *EMBIO (Euglena Marine Biofuel*

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This process flow illustrates an integrated pathway that converts oil derived from *Euglena* microalgae and used cooking oil (UCO) into “drop in” diesel/jet fuel that meets specifications. Starting with the inspection and blending of feedstocks, the stream is sequentially processed through pre-treatment, hydrothermal conversion, hydrotreating, and distillation to produce product fractions such as renewable diesel, SAF (Sustainable Aviation Fuel), and renewable naphtha. The final products are then stored, optionally blended with petroleum based fuels to meet target specifications, and distributed through existing supply networks ensuring compatibility with current engines and refueling infrastructure while aiming to reduce overall greenhouse gas intensity. The process *EMBIO (Euglena Marine Biofuel)* is as follows:

a. ***Feedstock sourcing***
Two inputs are prepared: microalgae-derived oil (Euglena) and used cooking oil (UCO). Each batch is checked for water, solids, free fatty acids, and metals.

b. ***Feedstock blending tank***
The two oils are metered and blended to reach a stable, consistent feed (target acidity, moisture, and viscosity) before upgrading.

c. ***Pre-treatment***
The mixed feed is degummed/neutralized, filtered, and dried. If needed, free fatty acids are reduced (e.g., by esterification) to protect downstream catalysts.

d. ***Hydrothermal conversion***
The pre-treated oil undergoes high-temperature, high-pressure water processing that starts deoxygenation and molecular rearrangement, making it suitable for catalytic upgrading.

e. ***Hydrotreating (hydrogenation)***
Over supported catalysts with hydrogen, the stream is deoxygenated (forming H_2O), desulfurized, and denitrogenated, while heavy molecules are saturated and partially cracked into the diesel/jet range.

f. ***Distillation***
The upgraded liquid is fractionated into product cuts typically renewable diesel (green diesel), sustainable aviation fuel (SAF/bio-jet), and renewable naphtha to meet fuel specifications.

g. ***Biofuel storage tank***
On-spec renewable product is stored and readied for blending or direct use, depending on the application and regulations.

h. ***Petroleum storage tank***
Conventional petroleum fuel is stored in parallel to enable controlled blending with the renewable stream.

i. ***Blended biofuel tank***
Renewable and petroleum streams are blended to the required specification (e.g., B5–B100 for diesel, ASTM compliant blends for jet fuel).

j. ***Distribution / delivery***
The finished blended biofuel is loaded to tanker trucks for delivery to end users (road fleets, aviation, marine bunkering), typically compatible with existing engines and infrastructure when within spec.

Illustrative Numerical Scenario

Assumptions (conservative, literature based):

- Areal productivity: 11 g m^{-2} d^{-1} dry biomass (semicontinuous raceway, nitrogen-managed)
- Base area: 1 ha = 10,000 m^2
- Operating days: 365 days/year
- Lipid/wax ester fraction: 30% (conservative) and 60% (optimistic)
- Biodiesel density: 0.88 kg/L

Calculations:

- Biomass per ha/year = 11 × 10,000 × 365 / 1000 = 40,150 kg DW (~40.15 t DW/ha/year)
- Oil yield 30% → 12,045 kg → volume ≈ 13,688 L/ha/year
- Oil yield 60% → 24,090 kg → volume ≈ 27,375 L/ha/year

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Interpretation: Conservative estimates produce ~13–27 m^3/ha/year, highlighting the need for large-scale cultivation or decentralized co-processing with local refineries to meet maritime fuel demand. Increasing areal productivity and wax ester fraction is critical for economic viability (Ogbonna et al., 2018).

Example feedstock cost (feedstock cost sensitivity)

Using DOE/BETO biomass benchmarks (~USD 674/ton AFDW), the estimated feedstock cost yields approximately USD 2.25/kg of oil, equivalent to ~USD 2.55/L for the biofuel feedstock alone. When compared to current marine fuel prices in Indonesia, this value is significantly higher: non-subsidized marine fuels such as biodiesel B40 or marine diesel equivalents are typically in the range of ~USD 1.30/L (≈ IDR 21,000/L), while lower-grade marine fuels (e.g., MFO) can be as low as ~USD 0.86/L (Solar Industri, 2025). This implies that the feedstock cost alone for Euglena-based biofuel is already about 2–3 times higher than conventional marine fuels, even before accounting for additional costs such as extraction, upgrading, CAPEX, O&M, and logistics. Consequently, achieving price competitiveness would require substantial policy support, including carbon pricing mechanisms (e.g., carbon credits in the range of ~USD 150–300/tCO_2 depending on lifecycle emissions savings), targeted subsidies, and co-product valorization strategies. This comparison highlights the critical economic gap that must be bridged to enable large-scale adoption of low-carbon marine biofuels in Indonesia's maritime sector.

Fuel quality & maritime compatibility

Wax ester-derived HEFA diesel exhibits low sulfur, good cetane numbers, and paraffinic characteristics, suitable for marine auxiliary engines. Cold-flow, lubricity, stability, and flash point must comply with ISO 8217 marine fuel standards. Sea trials, including MOL and Euglena Co., have validated operational viability for tugboats. Regulatory harmonization of fuel specifications and bunkering procedures is essential for broad deployment (MOL, 2019).

Environmental & economic tradeoffs

GHG reduction, when low-carbon electricity and waste CO_2 are used, life cycle GHG reductions of 40–70% are achievable. High carbon electricity or conventional drying routes can negate benefits. Integration of renewable electricity, DME wet extraction, and co-product valorization is key for net climate benefit (Davis et al., 2020). Economic bottlenecks, primary cost drivers include cultivation infrastructure, downstream dewatering/upgrading, and CAPEX for DME extraction. Co products (paramylon, protein) are critical to achieve acceptable economics**,** supporting a biorefinery model rather than a fuel only paradigm.

Optimization of EMBIO Byproducts: Paramylon & Protein

The production of *Euglena* Marine Biofuel (EMBIO) via the wax ester pathway generates two high-value byproducts paramylon and biomass protein. Optimizing these byproducts supports industrial downstreaming, boosts economic value, and advances the green economy in line with Asta Cita goals (industrialization & green economy) and SDGs 7 (Affordable & Clean Energy) and 13 (Climate Action).

a. Paramylon

A β-1,3-glucan polysaccharide stored in *Euglena* cells, appearing as microscopic granules, soluble in alkaline solutions, with strong bioactive properties.

Table 1. Applications Paramylon

APPLICATIONS PARAMYLON	
Products	**Benefits**
Pharmaceuticals & immune supplements	Immunomodulatory and antioxidant benefits
Bioplastics	Processed into plastics as a biodegradable petrochemical plastics alternative.
Eco-friendly cosmetics	Anti-aging creams, sunscreens, and UV-protective skincare

Optimization strategies include applying enzymatic or alkaline extraction to achieve over 90% paramylon purity, combined with biorefinery integration that reuses residual heat and energy from the biofuel process to maximize efficiency and sustainability.

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b. Biomass Protein

Protein-rich biomass (40–50% dry weight) remaining after oil extraction.

Table 2. Applications Biomass Protein

APPLICATIONS BIOMASS PROTEIN	
Products	**Benefits**
Aquaculture feed	Sustainable alternative to fishmeal.
Functional foods	Fortified biscuits, protein drinks, and other nutrition products.
Biofertilizers	Organic nitrogen source for agriculture.

Optimization strategies involve using ultrasonic or high-pressure cell disruption to enhance protein yield, combined with energy-efficient drying methods to maintain product quality.

c. Integrated Value in the EMBIO Chain

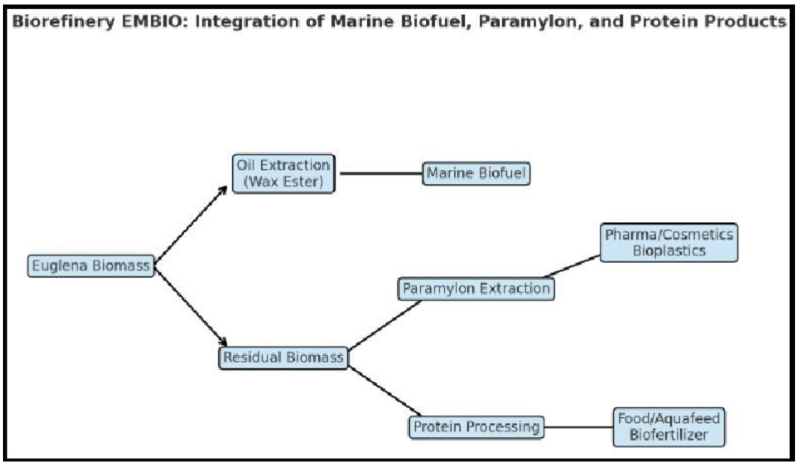

Figure 3. Flowchart Integrated Value in the EMBIO Chain

A zero-waste approach ensures that all *Euglena gracilis* biomass fractions are utilized, enabling the co-production of low-carbon fuels and high-value industrial products. Paramylon (β-1,3-glucan) has been widely recognized for its applications in pharmaceutical and cosmetic industries due to its antioxidant, antimicrobial, and therapeutic properties (Mezzanotte et al., 2026; Li et al., 2025). In addition, *E. gracilis* biomass contains proteins, lipids, and other metabolites that can be utilized in food, feed, and fertilizer sectors, highlighting its versatility as a biorefinery feedstock (Zhu et al., 2024; Kim et al., 2020). The integration of waste-based cultivation systems further supports circular economy principles by valorizing organic waste streams and CO_2 into valuable products, improving resource efficiency and reducing environmental impacts (Mou et al., 2024; Zhu et al., 2024). This integrated biorefinery concept enhances economic feasibility, creates bioindustry employment opportunities, and contributes to emission reductions across feed, chemical, and material supply chains.

CONCLUSIONS AND SUGGESTION

This study concludes that EMBIO (Euglena Marine Biofuel), produced through an integrated port scale system combining hybrid raceway fermenter cultivation, energy efficient DME wet extraction, catalytic upgrading to HEFA-type green diesel, and co-product valorization of paramylon and protein, holds strong potential as a drop in, low carbon alternative for the maritime sector. Its compatibility with existing bunkering infrastructure and marine engines enables rapid adoption, supporting Indonesia's green economy objectives (Asta Cita point 2) while achieving lifecycle GHG reductions of 40–70% under optimal integration with renewable electricity and waste CO_2. Beyond biofuel, paramylon and protein offer high value applications in bioplastics, pharmaceuticals, cosmetics, feed, food supplements, and biofertilizers, maximizing biomass utilization and strengthening the national bio based industry.

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In the Indonesian context, collaboration with Pertamina is pivotal, leveraging its refining, storage, and bunkering networks to scale both biofuel production and co-product processing near major ports such as Tanjung Priok, Tanjung Perak, and Belawan. Co-processing Euglena wax ester oil alongside paramylon and protein production in co-located facilities reduces logistics costs, supports industrialization, and advances downstream value creation (Asta Cita point 5). Adoption by the shipping industry starting with tugboats, ferries, and short-sea vessels can be accelerated through pilot-scale bunkering projects modeled after Japan's MOL Euglena tugboat trial, demonstrating both fuel performance and co- product market viability while aligning with IMO GHG targets and Indonesia's NDCs. Recommendations:

1. Pilot Biorefinery Facility, Pertamina in partnership with Indonesian ports and research institutions, should establish a pilot EMBIO biorefinery integrating marine biofuel production and co product processing (paramylon and protein) to validate supply chain logistics, ISO 8217 fuel compliance, co-product quality standards, and performance under local maritime conditions.
2. Policy Support, Develop fiscal incentives carbon credit schemes, renewable fuel mandates, and bio based product certification to enhance economic feasibility and accelerate market penetration of both biofuel and co- products.
3. R&D Focus, Advance research on high yield Euglena strains optimize wax ester, paramylon, and protein extraction, and integrate CO_2 capture from nearby industrial or power plant sources to achieve closed-loop sustainability.
4. Public Private Partnerships, Engage shipping operators, shipbuilders, agro- industrial sectors, and academia to expand both maritime fuel transition and co-product commercialization, ensuring alignment with national energy security, industrialization, and decarbonization targets.

By integrating EMBIO development with Pertamina's green energy roadmap and tapping co-product markets, Indonesia can lead in sustainable maritime fuels and bio-based industries, advancing environmental goals, economic growth, and innovation while supporting Asta Cita points 2 & 5 and SDGs 7 and 13.

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