



INTEGRATED ALGAL BIOREFINERY AND BIO-CIRCULAR-GREEN ECONOMY TO MEET THE AGENDA OF GLOBAL SUSTAINABLE DEVELOPMENT GOALS WITH CO-GENERATION OF BIOENERGY AND GREEN PRODUCTS

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A B S T R A C T

Carbon dioxide and methane emissions together with plastic pollution have become major global challenges. These have immensely contributed to the rise in climate disasters and have further exacerbated the wide gaps between the haves and the have-nots. Solutions must involve broad-based and multi-dimensional action plans, so that the agenda of global Sustainable Development Goals (SDGs) can be fully realized, beyond the confines of meeting rooms and lecture theatres. For effective climate actions, the development of an Integrated Algal-Oil Palm Biorefinery and Bio-Circular-Green (BCG) Economy frameworks for energy, bio/nanomaterials, biochemicals, environmental, and biomedical applications, are proposed as viable strategies. The prospects of algae for biofuels production, high-value chemicals, and waste valorization are elaborated. The integration of algal energy generation with nano-platforms to improve energy conversion, and for biomedical application including as potential adjuvant for targeted therapy are discussed. The socio-economic development based on HEESBA philosophy, derived from Arabic word "Hisbah" for "Accountability", which involves Bioenergy, Biomaterial, Biochemical and Education, is proposed. These could potentially serve as catalysts to create a new breed of entrepreneurs and communities that place importance on progress with social impact and wisdom intact, whilst reaping the Profit for the People and the Planet.



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1. INTRODUCTION

Integrated Bioferinery and BCG economy must be embraced as vital strategies to mitigate irreversible climate crisis, meet the Agenda of Global SDGs and thrive in this new "World-order" (Marshall et al., 2023; Abdullah et al., 2024). The rise in temperature, acidification and oxygen depletion of the ocean must be dealt with in such a way that the local impacts from the implementation of renewables are minimized (Pirttimaa & Cruz, 2020). Among renewables, solar, wind, hydrogen, hydropower, geothermal, and marine energy can be universally considered as "green" clean energy. For nuclear energy, due to the level of safety measures required, it is still considered a "red" clean energy, while bioenergy can be classified as "reasonably clean" green energy due to the release of absorbed photosynthetic CO₂ or CO upon fuel combustion. In the case of marine energy, the "green" and "red" levels can be interchangeable as technology improves.

Covering 70% of the Earth's surface and holding 97% of its water, the ocean and marine ecosystems have great potentials to provide abundant sources of energy in the form of tides, waves, currents and water flows into rivers, lakes or channels, as well as changes in temperature, salinity or pressure (NREL, n.d.). Marine energy involves the extraction of energy from the ocean, making use of waves, tidal and kinetic energy to generate power. The movements in installed devices convert the kinetic energy into electrical power (NREL, n.d.). At present, there is a total lack of data to understand the short- and long-term effects of collision risks, noise, electromagnetic waves and changes in habitat and animal behavior during the installation, operation and presence of added structures or devices in the ocean environment (Pirttimaa & Cruz, 2020).

The urgency of these challenges is underscored by the accelerating pace of climate disruption and the narrowing window to achieve Net Zero Emissions (NZE) by 2050. As the clock is ticking, the global energy transition must not only decarbonise rapidly but also ensure that the pathways chosen are socially inclusive, economically viable and ecologically sound. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasised that without immediate and deep emissions reductions across all sectors, limiting global warming to 1.5°C will be beyond reach. In this context, the ocean—often overlooked in energy debates—emerges as a critical frontier for sustainable energy generation and carbon management.

However, the deployment of ocean energy technologies has been hampered by a combination of high investment costs, technological immaturity, lengthy bureaucratic consenting processes, and the absence of dedicated legislation and regulatory frameworks (Pirttimaa & Cruz, 2020). Unlike solar and wind, which have benefitted from decades of policy support and market maturation,

marine energy still lacks the extensive monitoring data and spatial planning instruments necessary to assess and mitigate environmental impacts. This regulatory and knowledge gap has slowed commercial deployment and deterred investment, despite the vast theoretical potential of ocean-based energy systems.

It is within this broader context that bioenergy and bioproducts derived from marine bioresources offer a distinctly different and potentially more compatible pathway. Bioenergy is sourced from biomass that contains carbon assimilated through photosynthesis, and the carbon is released back into the atmosphere during combustion, making it a nearly zero-emission fuel. Bioenergy already accounts for 55% of global renewable energy and over 6% of global energy supply, and this is expected to increase by 8% annually to meet the NZE scenario in 2030 (IEA, n.d.). There is greater flexibility to use existing legislation for algal bioproducts (BIM, 2023), in comparison to the requirements for marine spatial planning, extensive monitoring data, lengthy bureaucratic consenting processes and dedicated legislation specifically for ocean energy (Pirttimaa & Cruz, 2020). Sustainable energy production and bioproducts based on the marine ecosystem must be addressed within the context of the Climate-Energy-Food-Water-Socio/Economy Nexus (Abdullah et al., 2024). Macroalgae and microalgae as bioresources, natural to the marine ecosystem, can be developed to meet the food and socio-economic agenda by an integration with community development programme, environmental remediation and waste valorization, and clean/bioenergy co-generation based on biodiesel, bioethanol, biomethane, biohydrogen, bio-oil, and sustainable aviation fuel, with solar, energy storage and supercapacitors (Abdullah et al., 2024; Ali et al., 2024). The global seaweed and microalgae production was recorded at 35.8 million tonnes in 2019, with 97% of the production coming from cultivation (FAO, 2021). Rapid progress has been made in the method of cultivation, processing, product development and waste utilization (Zhang et al., 2022). Inshore cultivation at sea depths of 5–50 meters is the main method (mariculture), while semi-floating and supporting rafts, sheets or nets are used in intertidal sea areas with lower impact from marine turbulence (Zhang et al., 2022; McElligott et al., 2022). For off-shore deep-seawater culture, floating rafts or long ropes are used, but these can be expensive for breeding, requiring specific varieties and the need for technology to manage uncertainties from wind, waves, diseases and pests. To allow real-time monitoring, cultivation in tanks, lagoons, and ponds is simple, although it may be costly for mass production due to the scarcity of land and water. Integrated High-Rate Algal Ponds (HRAP) for wastewater treatment and algae production are suitable for large-scale aquaculture in ponds and lakes. Sea-based or land-based cultivation of multi-species at different levels of the food requirement based on Integrated Multi-Trophic Aquaculture (IMTA) systems is carried out on the same site or in close proximity, providing space for

fish to grow alongside algae, sea cucumbers or urchins, or mussels and scallops, that can feed on fish wastes or dissolved nutrients (Zhang et al., 2022; BIM, 2023). With the method and technological advancement, HRAP and IMTA are suitable for implementation at a larger industrial scale. However, there are greater needs for improvements in seedling technology for continuous supply of seaweed seedlings to meet the demand (Zhang et al., 2022; McElligott et al., 2022).

The objective of this review article is to highlight eco-friendlier, and environmentally compatible forms of marine energy by harnessing macroalgae and microalgae in a bio refinery platform. Additionally, it aims to incorporate a community development program to benefit the coastal community specifically and the lower-income group in general. By synthesising recent advances in algal cultivation, biorefinery design, waste valorisation, nanotechnology-enabled processing, and socio-economic integration, this review seeks to demonstrate how an integrated algal biorefinery—anchored in the principles of the Bio-Circular-Green (BCG) economy—can simultaneously address energy security, environmental remediation, and community development. The review is structured as follows: Section 2 examines bio/clean energy from macroalgae and microalgae; Section 3 addresses waste remediation and valorisation; Section 4 discusses the alignment with the Agenda of Global SDGs and the role of nanotechnology and community programmes; and Section 5 concludes with recommendations for resilient and adaptable biorefinery design.

2. BIO/CLEAN ENERGY

As the clock is ticking to achieve Net Zero Emissions (NZE) by 2050 and meet the Agenda of Global SDGs, bioenergy from the marine eco-system offers greater biocompatibility with the environment. Bioenergy is sourced from biomass that contains carbon assimilated through photosynthesis, and the carbon is released back into the atmosphere during combustion making it a nearly zero-emission fuel. Bioenergy already accounts for 55% of global renewable energy, and over 6% of global energy supply. This is expected to increase by 8% annually to meet the NZE scenario in 2030 (IEA, n.d.). There is greater flexibility to use existing legislation for algal bioproducts (BIM, 2023), in comparison to the requirements for marine spatial planning, extensive monitoring data, lengthy bureaucratic consenting processes and dedicated legislation specifically for ocean energy (Pirttimaa & Cruz, 2020). Sustainable energy production, and bioproducts based on the marine eco-system must be addressed within the context of the Climate-Energy-Food-Water-Socio/Economy Nexus (Abdullah et al., 2024). Macroalgae and microalgae as bioresources, natural to the marine ecosystem, can be developed to meet the food and socio-economic agenda by an integration with community development programme, environmental remediation and waste

valorization, and clean/bioenergy co-generation based on biodiesel, bioethanol, biomethane, biohydrogen, bio-oil, and sustainable aviation fuel, with solar, energy storage and supercapacitors (Abdullah et al., 2024; Ali et al., 2024).

2.1 Biofuels and bioproducts from Macroalgae

The global seaweed and microalgae production was recorded at 35.8 million tonnes in 2019, with 97% of the production coming from cultivation (FAO, 2021). Rapid progress has been made in the method of cultivation, processing, product development and waste utilization (Zhang et al., 2022). Inshore cultivation at sea depths of 5-50 meters is the main method (mariculture), while semi-floating and supporting rafts, sheets or nets are used in intertidal sea areas with lower impact from marine turbulence (Zhang et al., 2022; McElligott et al., 2022). For off-shore deep-seawater culture, floating rafts or long ropes are used, but these can be expensive for breeding, requiring specific varieties and the need for technology to manage uncertainties from wind, waves, diseases and pests. To allow real-time monitoring, cultivation in tanks, lagoons, and ponds is simple, although it may be costly for mass production due to the scarcity of land and water. Integrated High-Rate Algal Ponds (HRAP) for wastewater treatment and algae production are suitable for large-scale aquaculture in ponds and lakes. Sea-based or land-based cultivation of multi-species at different levels of the food requirement based on Integrated Multi Trophic Aquaculture (IMTA) systems is carried out on the same site or in close proximity, providing space for fish to grow along-side algae, sea cucumbers or urchins, or mussels and scallops, that can feed on fish wastes or dissolved nutrients (Zhang et al., 2022; BIM, 2023). With the method and technological advancement, HRAP and IMTA are suitable for implementation at a larger industrial scale. However, there are greater needs for improvements in seedling technology for continuous supply of seaweed seedlings to meet the demand (Zhang et al., 2022; McElligott et al., 2022).

Macroalgae are feasible for use in industrial-scale carbon sequestration, and as feedstocks for biofuels, high-value chemicals (HVC) and biomaterials (Lomartire et al., 2022; Kadell & Callychurn, 2023; Johnston et al., 2023). Coastal marine biorefineries may utilize macroalgae and marine organisms for cost-effective biofuel co-generation with HVC and atmospheric Carbon Capture and Storage (CCS). Based on the area of the farms and the species, it is estimated that 100 Gtons of CO₂ can be removed between 4-month to 12-year period, with the co-production of 8 trillion liters of ethanol (ETH) and HVC of commercial interest (Johnston et al., 2023). Species such as *Gracilaria salicornia* and *Ulva lactuca* effectively produce gel or substitutes for starch as biomaterials for improved tensile strength and better water absorptivity, with properties comparable to petroleum-based plastics, while at the same time

biodegradable (Lomartire et al., 2022; Kadell & Callychurn, 2023).

2.2 Biofuels and bioproducts from Macroalgae

Microalgal feedstock is ideal for co-production of biodiesel and bioethanol (bioETH). Acid hydrolysis pretreatment of *Scenedesmus* sp. achieves a 93% yield of sugar release, relative to the total sugar content in the untreated control sample. Fermentation of the hydrolysate using *Saccharomyces cerevisiae* results in an 86% ETH yield (based on theoretical conversion of fermentable sugars present in the hydrolysate). Enzyme-catalysed direct transesterification of *Scenedesmus* sp. biomass in dimethyl carbonate (DMC) as a solvent, produces 92% methyl esters (ME), 1.9% glycerol carbonate and 4.9% glycerol decarbonate. Direct transesterification, followed by ETH fermentation produces a 92% yield of ME based on lipid content, and a 93% ETH yield based on fermentable sugars in the hydrolysate (Sivaramakrishnan & Incharoensakdi, 2018). ETH is advantageous as it can dissolve both polar and non-polar compounds. The ETH and water extracts of *Nannochloropsis oculata* and *Chlorella* sp. at 1:2 and 1:3 ratios to tamoxifen (TMX), a breast-cancer drug, exhibit high cytotoxicity against breast cancer cells MCF-7 (15.8-29.5 µg/mL) and against 4T1 cells (a model for metastasized human breast cancer) (13.8-31.6 µg/mL), while showing low cytotoxicity against non-cancerous Vero cells (24.5-85.1 µg/mL). The ¹H NMR metabolomics analysis suggests a significant level of violaxanthin, triglycerides, stearic acids and eicosapentaenoic acid (EPA) in the ETH extracts. The water extracts contain fewer compounds than ETH, but interestingly exhibit unique presence of alanine, alongside oleic, linoleic, lactic and fumaric acids (Hussein et al., 2022).

3. WASTE REMEDIATION AND VALORIZATION

The algal consortium of *Chlorella* sp. and *Scenedesmus* sp. grow well in 75% diluted domestic wastewater, resulting in 1.78 g/L of biomass and 34.8% lipid content (with 51.8% palmitic acid, and 35.5% oleic acid), 27 mg/L of chlorophyll, and 0.175 g/L of protein. Algal growth on wastewater nutrients removes approximately 83% of COD, 86% of TOC, and 94% of TN. The deoiled biomass waste can be developed as biofertilizer (Silambarasan et al., 2021). Palm oil mill effluent (POME) treatment with the combination of empty fruit bunch (EFB) fibers, sludge inoculum and algal species at an optimal level achieves high biomethane production (4606-5296 mL CH₄/L POME/day), with equally high removal of BOD (83-98%) and COD (83-98%) (Ahmad et al., 2014, 2015). At 10% POME in seawater, the cell growth and lipid content, respectively, of *N. oculata* (0.21/day, 39.1%) and *T. suecica* (0.20/day, 27%) are enhanced, with high palmitic acid recorded at 28.2% and 36.5%, respectively (Shah et al., 2016). Hydrothermal

liquefaction (HTL) is effective in converting high-moisture microalgal feedstock, without the need for an energy-intensive dewatering step (Khalekuzzaman et al., 2024). Co-HTL of microalgae grown on wastewater and domestic sewage sludge has resulted in a 39% biocrude yield (Mishra & Mohanty, 2020), while co-HTL of wastewater-grown microalgae and peat has produced a 37% yield with naphtha as the major component of the lighter biocrude (Hossain et al., 2022). Feedstock-derived naphtha not only exhibits fuel compatibility and versatility with high-energy density but also provides an economically viable route to reduce Greenhouse gas (GHG) emissions due to its carbon-neutrality (Khalekuzzaman et al., 2024).

4. MEETING THE AGENDA OF GLOBAL SDGS

Integrating nanotechnology-driven Algal Biorefinery within BCG Economy initiative is an innovative solution to improve economic viability by optimizing different stages of biomass processing and biofuel production. This could support SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action). Nanotechnology plays crucial role in enhancing microalgal cell growth by 20–30%, increasing biocompound accumulation, facilitating cell wall disruption and extraction, and improving harvesting efficiency by 80–99%, with conversion efficiency up to 85–99%. The applications of metal oxides, mesoporous materials, and carbon-based nanocatalysts elevate lipid conversion and transesterification into biodiesel, while nano-biocatalysts attain improved enzyme activity and stability for higher yields of bioethanol, biohydrogen, and biogas (Ali et al., 2024).

The scale of marine biorefineries must be significantly increased to an industrial scale by adopting reasonable technological development to produce bioenergy and bioproducts. The implementation of biomass conversion and waste utilization within an Integrated Algal-Oil Palm Biorefinery framework could improve the economics of sustainable energy production with biomaterial, biochemical and agro-product co-generation (Abdullah et al., 2024). As shown in Fig. 1, the use of natural sunlight instead of artificial light, and wastewater instead of fresh water, are examples of viable routes to be taken. Community development and training programs involving smart agriculture and aquaculture, and activities such as waste collection, utilization and conversion, add values to the biorefineries for macroeconomic growth (Wiggins et al., 2010; Gajaria et al., 2017; Abdullah et al., 2024).

There is now an increasing interest to utilize Solid Lipid Nanoparticles as versatile nano-carriers for a wide range of applications in agriculture and the environment, cosmetics, wound healing, malarial treatment, gene therapy and nano-vaccines, and targeted cancer therapy

(Hussein et al., 2025). Sustainable and nature-based solutions put great emphasis on the adoption of natural principles to attain a balance between production, consumption, waste generation, processing and recycling. Even highly biodegradable microplastics, despite lower aquatic ecotoxicity, are shown to emit higher greenhouse gases than engineered biodegradation such as via anaerobic digestion (Piao et al., 2024). The alternative routes may lie in systematic, large-scale and commercial algal cultivation (Lomartire et al., 2022; Kadell & Callychurn, 2023; Abdullah et al., 2024), and

tree planting for CO₂ removal, and for timber, wood chips, natural sorbents, paper making, biocomposites and packaging materials. Cultivation of *Corchorus capsularis* L. or *C. olitorius* L. (jute) and *Hibiscus cannabinus* L. or *H. sabdariffa* L. (kenaf) (Rowell & Stout, 2007), *Ceiba pentandra* L. (kapok) (Abdullah et al., 2010), and *Eucalyptus* species (Pirrhalho et al., 2014), should embrace sustainable agro practices on unused and idle-lands, without resorting to massive deforestation and land clearing as observed with many mono-crop cultivation.

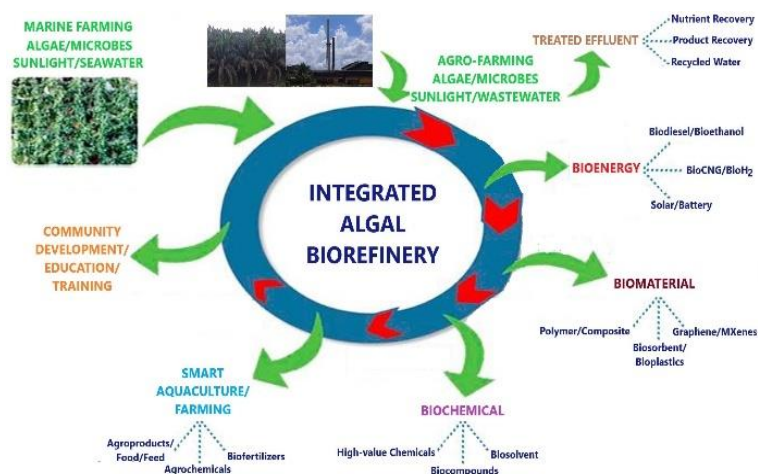


Figure 1. Integrated Algal Biorefinery for Sustainable Energy, Bioproducts Co-generation and Community Development Programs (Modified from Gajaria et al., 2017; Abdullah et al., 2024)

The cultivation of crops for the supply of biomaterials can be implemented within the Integrated Biorefinery set-up. However, the rise in sea levels and desertification from extreme heat, together with the threat of pests and diseases, have impacted irrigation and productivity, leading to crises in food crop production and major economic losses. Since all major crops are salt-sensitive, large tracts of agricultural land may be rendered unusable due to irrigation-induced soil salinization. To counter this, the development of salt, pest and disease tolerant plants is applicable strategy. Both sophisticated irrigation techniques and breeding of salt-tolerant crops via over-expression of ion transporters are among approaches taken to increase salt tolerance. *Thellungiella halophila*, for example, exhibits slower transpiration under salt-stress while maintaining high water uptake and ion transport (Volkov et al., 2004).

To fight poverty, considering the largely agrarian community in the developing world, investment in bioenergy is the only logical way forward, at least before fully embracing other clean energy portfolios. The “HEESBA” (ح س ب أ) philosophy (for Health-consciousness, Environmental and Safety awareness, Energy sufficiency, Social-inclusiveness, Business acumen, and Adaptability and Agility) which promotes the 4 diamonds to be polished, namely - Bioenergy, Biomaterial, Biochemical and Education (Abdullah et al., 2024), can leverage BCG economy as the driver of an integrated algal biorefinery. This can utilize the

production of biodiesel, bioethanol and biogas and co-generation of biopolymers, biocomposites, and HVCs in parallel with waste conversion, recycling, and reutilization as the prime movers. The community development programme may involve training on crop diversification, soil health rehabilitation and maintenance, aquaculture, and recycling and composting to enhance knowledge and skills, and diversify economic activities and bring new green products into the market. These should aim to create scalable economic opportunities and train new entrepreneurs, reduce the rate of unemployment, draw the youths away from undesirable activities, raise the status of agricultural sector as potential lucrative business venture, and indirectly halt expansion of plantation into the virgin forests. The concept aligns well with the principles of resource efficiency and contributes towards a closed-loop system to minimize environmental impact and maximize socio-economic benefits.

5. CONCLUSION

Ocean energy is an important source of renewable energy to mitigate climate disaster. Challenges related to investment costs, technology development, perceptions of interference with the natural ecosystem, and legislation and regulatory frameworks, however, have greatly hampered rapid deployment. Bioenergy and bioproducts from marine bioresources are more compatible with the ecosystems to meet the Agenda of

Global SDGs, and market demands for bio-based products. It is pertinent to improve the technologies for seedling nurseries, and the mode of algal cultivation, harvesting and processing. Integrated algal biorefineries should be designed to be resilient and adaptable with inclusive community programs as climate change and seawater contamination may eventually impact the overall development, the economics and social wellbeing.

This review has demonstrated that macroalgae and microalgae, as bioresources natural to the marine ecosystem, offer a viable and environmentally compatible route to co-generate bioenergy and high-value bioproducts within an integrated biorefinery platform. Macroalgae such as *Gracilaria salicornia* and *Ulva lactuca* have been shown to produce gel or starch substitutes with tensile strength and water absorptivity comparable to petroleum-based plastics, while remaining biodegradable (Lomartire et al., 2022; Kadell & Callychurn, 2023). Coastal marine biorefineries utilising macroalgae and marine organisms have the potential to remove an estimated 100 Gtons of CO₂ over a 4-month to 12-year period, with the co-production of 8 trillion litres of ethanol (ETH) and high-value chemicals (HVC) of commercial interest (Johnston et al., 2023). Similarly, microalgal feedstock has proven ideal for co-production of biodiesel and bioethanol (bioETH), with acid hydrolysis pretreatment of *Scenedesmus* sp. achieving 93% sugar release and fermentation yielding 86% ETH (Sivaramakrishnan & Incharoensakdi, 2018). Enzyme-catalysed direct transesterification in dimethyl carbonate (DMC) has further produced 92% methyl esters (ME), 1.9% glycerol carbonate and 4.9% glycerol decarbonate, while ETH and water extracts of *Nannochloropsis oculata* and *Chlorella* sp. have exhibited high cytotoxicity against breast cancer cells MCF-7 and 4T1, with low toxicity against non-cancerous Vero cells (Hussein et al., 2022).

The integration of waste remediation and valorisation into the biorefinery framework has also been substantiated. The algal consortium of *Chlorella* sp. and *Scenedesmus* sp. grown in 75% diluted domestic wastewater achieved 1.78 g/L biomass and 34.8% lipid content, with approximately 83% COD, 86% TOC and 94% TN removal, and the deoiled biomass waste developed as biofertilizer (Silambarasan et al., 2021). Palm oil mill effluent (POME) treatment combined with

empty fruit bunch (EFB) fibres, sludge inoculum and algal species achieved high biomethane production (4606–5296 mL CH₄/L POME/day) with equally high BOD and COD removal (83–98%) (Ahmad et al., 2014, 2015). Hydrothermal liquefaction (HTL) has proven effective for high-moisture microalgal feedstock without energy-intensive dewatering, with co-HTL of wastewater-grown microalgae and sewage sludge yielding 39% biocrude (Mishra & Mohanty, 2020), and co-HTL with peat producing 37% yield with naphtha as the major lighter biocrude component (Hossain et al., 2022; Khaleukzaman et al., 2024).

Nanotechnology-driven algal biorefinery within the BCG Economy initiative has emerged as an innovative solution to improve economic viability, enhancing microalgal cell growth by 20–30%, harvesting efficiency by 80–99%, and conversion efficiency up to 85–99%, thereby supporting SDG 7, SDG 9 and SDG 13 (Ali et al., 2024). The implementation of biomass conversion and waste utilisation within an Integrated Algal-Oil Palm Biorefinery framework, as illustrated in Fig. 1, can improve the economics of sustainable energy production with biomaterial, biochemical and agro-product co-generation (Abdullah et al., 2024). Community development and training programmes involving smart agriculture and aquaculture, and activities such as waste collection, utilisation and conversion, add values to the biorefineries for macroeconomic growth (Wiggins et al., 2010; Gajaria et al., 2017; Abdullah et al., 2024). The "HEESBA" philosophy, promoting the 4 diamonds to be polished Bioenergy, Biomaterial, Biochemical and Education can leverage BCG economy as the driver of an integrated algal biorefinery, utilising biodiesel, bioethanol and biogas production and co-generation of biopolymers, biocomposites and HVCs in parallel with waste conversion, recycling and reutilisation as prime movers (Abdullah et al., 2024). Such community programmes may involve training on crop diversification, soil health rehabilitation, aquaculture, and recycling and composting, aiming to create scalable economic opportunities, train new entrepreneurs, reduce unemployment, draw youths away from undesirable activities, and indirectly halt expansion of plantation into virgin forests. The concept aligns well with the principles of resource efficiency and contributes towards a closed-loop system to minimise environmental impact and maximise socio-economic benefits.

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APPENDIX:

Abbreviations

BOD	Biological Oxygen Demand	EFB	Empty Fruit Bunch	IMTA	Integrated Multi Trophic Aquaculture
CCS	Carbon Capture and Storage	EPA	Eicosapentaenoic acid	ME	Methyl esters
CNG	Compressed Natural Gas	ETH	Ethanol	NZE	Net Zero Emissions
CO ₂	Carbon dioxide	H ₂	Hydrogen	POME	Palm Oil Mill Effluent
CO	Carbon monoxide	¹ H NMR	Proton Nuclear Magnetic Resonance	SDG	Sustainable Development Goals
COD	Chemical Oxygen Demand	HRAP	High-Rate Algal Ponds	TMX	Tamoxifen
CH ₄	Methane	HTL	Hydrothermal Liquefaction	TN	Total Nitrogen
DMC	Dimethyl carbonate	HVC	High-value chemicals	TOC	Total Organic Carbon

