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Can Sri Lanka Become a Regional Hub for Algal Biodiesel Production? A Critical Review of Ecological Potential, Technological Readiness, and Future Prospects

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Abstract

Sri Lanka's dependence on imported fossil fuels and its abundant aquatic resources have generated increasing interest in algal biodiesel as a sustainable third-generation biofuel. This review critically evaluates the country's potential to develop a commercially viable algal biodiesel sector by synthesizing evidence on ecological suitability, indigenous algal resources, technological readiness, sustainability benefits, and commercialization challenges. Sri Lanka possesses favorable climatic conditions, diverse freshwater and marine ecosystems, and several indigenous microalgal and macroalgal species with promising lipid productivity. However, comparison with international experience demonstrates that favorable natural resources alone are insufficient for commercialization because harvesting costs, downstream processing, economic viability, and policy support remain major constraints. The review identifies critical research gaps in pilot-scale cultivation, techno-economic assessment, life-cycle analysis, and strain improvement, and proposes strategic priorities including integrated biorefineries, wastewater-based cultivation, industrial CO_2 utilization, and supportive policy frameworks. These coordinated interventions are essential for positioning Sri Lanka as a competitive regional hub for sustainable algal biodiesel production.

Keywords: algal biodiesel, Sri Lanka, renewable energy, microalgae, commercialization

1. Introduction

The global transition towards sustainable and low-carbon energy systems has intensified research on renewable alternatives to petroleum-derived transportation fuels. Biodiesel has emerged as one of the most promising renewable liquid fuels because of its biodegradability, low Sulphur content, compatibility with existing diesel engines, and potential to reduce greenhouse gas emissions. However, conventional first-generation biodiesel feedstocks, including palm oil, soybean,

rapeseed, and coconut oil, continue to raise significant concerns regarding competition with food production, extensive land and freshwater requirements, biodiversity loss, and indirect land-use change (Purnama *et al*., 2025). Consequently, increasing attention has shifted towards third-generation biofuels derived from microalgae and macroalgae, which can be cultivated on non-arable land using freshwater, brackish water, seawater, or wastewater while exhibiting substantially higher biomass and lipid productivities than terrestrial oil crops (Mahmood et al., 2023; Maliha & Abu-Hijleh, 2023; Sarwer *et al*., 2022). In addition to biodiesel production, algae provide multiple environmental benefits, including carbon dioxide sequestration, wastewater remediation, and the generation of value-added bioproducts, making them attractive components of emerging circular bioeconomy strategies (Ighalo *et al*., 2022; Nguyen *et al*., 2022). Nevertheless, despite decades of research and substantial investments in countries such as the United States, China, Australia, India, and several European nations, commercial-scale algal biodiesel production remains limited because of persistent technological, economic, and policy constraints associated with cultivation, harvesting, downstream processing, and overall process economics (Carneiro *et al*., 2017; Collet *et al*., 2014; Osman *et al*., 2024). These international experiences demonstrate that favorable biological characteristics alone are insufficient to establish a commercially sustainable algal biodiesel industry.

Sri Lanka possesses several natural advantages that could support the development of algae-based biodiesel. Its tropical climate, year-round solar irradiance, consistently warm temperatures, and extensive network of freshwater reservoirs, irrigation tanks, lagoons, estuaries, and coastal waters provide favorable conditions for continuous algal cultivation throughout the year (Sendanayake *et al*., 2015; Shelton *et al*., 2022). Furthermore, the country harbors a rich diversity of indigenous microalgae and macroalgae, including *Chlorella*, *Scenedesmus*, *Desmodesmus*, *Oscillatoria*, *Nannochloropsis*, *Sargassum*, and *Ulva*, several of which have demonstrated promising lipid contents and favorable fatty acid profiles for biodiesel production under laboratory conditions (Fuad Hossain *et al*., 2020; Sandani *et al*., 2020; Vimali *et al*., 2022). These resources, together with increasing concerns regarding national energy security and dependence on imported petroleum, have stimulated growing research interest in algal biofuels. However, most Sri Lankan studies have primarily focused on species identification, cultivation, lipid extraction, or laboratory-scale biodiesel production. Comparatively little attention has been devoted to evaluating technological readiness, economic feasibility, policy requirements, environmental sustainability, or the lessons that can be learned from international commercialization efforts. Consequently, although Sri Lanka possesses considerable ecological

potential, its realistic capacity to establish a commercially viable algal biodiesel industry has not yet been comprehensively or critically evaluated.

Therefore, this review critically assesses whether Sri Lanka's ecological and biological advantages can realistically be translated into a sustainable and commercially viable algal biodiesel industry. Unlike previous studies that mainly describe algal cultivation techniques or biodiesel production technologies, this review integrates evidence on ecological suitability, indigenous algal diversity, technological readiness, sustainability benefits, commercialization barriers, and future development priorities within the specific context of Sri Lanka. Particular emphasis is placed on comparing Sri Lanka's current position with international experience to identify the technological, economic, and policy factors that continue to limit large-scale commercialization worldwide. By synthesizing both national and international evidence, this review identifies key research gaps and strategic priorities that must be addressed to support future pilot-scale implementation, industrial development, and policy formulation. The paper is organized as follows. Section 2 examines Sri Lanka's ecological suitability and indigenous algal resources for biodiesel production. Section 3 reviews the technological pathways and current state of algal biodiesel research in Sri Lanka. Section 4 evaluates the sustainability benefits and circular bioeconomy opportunities associated with algal biodiesel development. Section 5 critically discusses the technological, economic, and policy challenges affecting commercialization by comparing Sri Lanka with international experience. Finally, Section 6 presents future research priorities, strategic recommendations, and the main conclusions.

2. Ecological Potential and Indigenous Algal Resources for Biodiesel Production in Sri Lanka

Sri Lanka possesses several natural advantages that favor year-round algal biomass production. Its tropical geographical location, consistently high solar irradiance, warm temperatures, abundant freshwater resources, and extensive coastline provide favorable environmental conditions for the cultivation of both microalgae and macroalgae. Unlike temperate countries that experience pronounced seasonal fluctuations, Sri Lanka's relatively stable climatic conditions permit continuous biomass production with comparatively lower seasonal variation. These characteristics have attracted increasing research interest in evaluating indigenous algal resources for biofuel production and other biorefinery applications. However, while ecological suitability provides an important foundation for algal cultivation, international experience demonstrates that natural resource availability alone is insufficient for successful commercialization. Therefore, Sri Lanka's environmental

advantages should be evaluated together with technological, economic, and policy considerations when assessing its long-term potential for algal biodiesel production.

2.1 Climatic Factors Supporting Algal Growth in Sri Lanka

Temperature and solar irradiance are among the most important environmental factors influencing algal photosynthesis, biomass productivity, lipid accumulation, and overall biodiesel yield. Sri Lanka is situated within the tropical belt (5°–10° N) and experiences relatively stable climatic conditions throughout the year, with average temperatures generally ranging between 27 and 30 °C across most parts of the country (Hossain *et al*., 2017). These temperatures closely match the optimum growth range reported for many commercially important microalgal species, which typically lies between 25 and 32 °C (Juneja *et al*., 2013).

Similarly, Sri Lanka receives consistently high solar irradiance, frequently exceeding 4-5 kWh m^{-2} day^{-1} (Wijesena & Asinghe, 2018; Sendanayake *et al*., 2015). Continuous sunlight availability supports high photosynthetic efficiency and prolonged cultivation periods compared with many temperate regions where biomass production is constrained by seasonal reductions in temperature and daylight hours. Furthermore, the country's bimodal monsoon system replenishes freshwater resources while maintaining favorable conditions across numerous reservoirs, irrigation tanks, lagoons, and coastal ecosystems (Shelton *et al*., 2022). Seasonal runoff also contributes nitrogen- and phosphorus-rich inputs into many aquatic systems, naturally enhancing algal productivity in several inland water bodies.

Although these climatic characteristics provide clear ecological advantages, they should not be interpreted as guarantees of commercial success. Countries such as India, northern Australia, and southern China possess comparable climatic conditions and have invested substantially in algal biotechnology; nevertheless, large-scale commercialization remains limited because of high production costs and technological constraints (Carneiro *et al*., 2017; Osman *et al*., 2024). Therefore, Sri Lanka's favorable climate should be regarded as an enabling factor that supports algal cultivation rather than as the sole determinant of a successful biodiesel industry.

2.2 Diversity of Aquatic Habitats Suitable for Algal Cultivation

Sri Lanka possesses a remarkable diversity of aquatic ecosystems that provide suitable habitats for both freshwater and marine algae. Freshwater reservoirs, irrigation tanks, rivers, lagoons, estuaries, and coastal waters collectively offer numerous opportunities for large-scale cultivation under different environmental conditions.

The country's ancient tank cascade systems together with major reservoirs such as Victoria, Randenigala, and Parakrama Samudra support diverse phytoplankton communities dominated by genera including *Chlorella*, *Scenedesmus*, *Desmodesmus*, *Ankistrodesmus*, and *Oscillatoria* (Silva *et al*., 2013). Many of these genera are internationally recognized as promising biodiesel feedstocks because of their rapid growth and relatively high lipid accumulation.

Sri Lanka's coastline, extending over 1,300 km, contains numerous lagoons, estuaries, and sheltered bays that support both marine microalgae and macroalgae. Species such as *Nannochloropsis*, *Tetraselmis*, *Gracilaria*, *Sargassum*, *Turbinaria*, and *Ulva* have been reported from these environments and exhibit desirable characteristics including tolerance to fluctuating salinity, robust biomass production, and suitability for biorefinery applications (Schubert *et al*., 2010; Coppejans *et al*., 2009; Fernando & Ranganathan, 2019).

Macroalgal resources are particularly abundant in the northern and northwestern coastal regions, including Jaffna, Mannar, Kalpitiya, and Trincomalee, where seasonal blooms of brown seaweeds such as *Sargassum* and *Turbinaria* provide substantial biomass resources. These species have attracted increasing international attention because hydrothermal liquefaction enables direct conversion of wet macroalgal biomass into biocrude without the energy-intensive drying required for conventional biodiesel production (Venkatachalam *et al*., 2021; Allen & Pearce, 2024).

2.3 Indigenous Algal Species with Biodiesel Potential

Sri Lanka's rich algal biodiversity represents one of its most valuable resources for future biofuel development. Laboratory investigations have demonstrated that several indigenous microalgal species possess favorable lipid contents and fatty acid compositions suitable for biodiesel production. Species including *Chlorella hemisphere*, *Desmodesmus* sp., *Scenedesmus dimorphus*, *Oscillatoria* sp., and *Nannochloropsis* sp. have reported lipid contents generally ranging from 20-40%, with some strains exhibiting even higher values under nutrient-limited cultivation (Sandani *et al*., 2020; Fuad Hossain *et al*., 2020; Premaratne *et al*., 2021). Their fatty acid profiles are typically dominated by palmitic, oleic, and linoleic acids, which contribute to favorable fuel properties such as satisfactory cetane number, oxidative stability, and combustion performance.

The biodiesel potential of indigenous microalgae that have been experimentally investigated in Sri Lanka is summarized in Table 1. The table compiles published case studies on native algal species, highlighting their reported distribution, ecological characteristics, lipid yield, and corresponding references. These studies

provide the strongest available evidence supporting the feasibility of utilizing locally available microalgae as biodiesel feedstocks under Sri Lankan conditions.

Table 1. Summary of published Sri Lankan studies investigating indigenous microalgal species for biodiesel production.

Algae Species	**Reported distribution in Sri Lanka**	**Ecology**	**Lipid yield**	**References**
Chlorella homosphaera	Beira lake, Colombo	Freshwater and marine *environment*	39.8%	Sandani *et al*., 2020
***Chlorella* sp.**	Victoria reservoir, Central province and Ulhitiya reservoir, Uva province	Terrestrial habitats of polar and temperate zones, in marine and freshwater habitats.	-	Kalana *et al*., 2016
***Desmodesmus* sp.**	Beira lake, Colombo	Thrives in freshwater and in hot subtropical water bodies.	31.46%	Maduwanthi *et al*., 2019
***Leptolyngbya* sp.**	Kandy	Salt marshes, salt pans, mangrove lagoons	21.15%	Hossain *et al*., 2020, Bowange *et al*., 2022
***Limnothrix* sp.**	Kandy	Salt marshes, salt pans	20.73%	Hossain *et al.*, 2020, Bowange *et al.*, 2022
***Lyngbya* sp.**	Kandy	Salt marshes, salt pans	16.05%	Hossain *et al*., 2020, Bowange *et al*., 2022
Monoraphidium sp.	Victoria reservoir, Central province and Ulhitiya reservoir, Uva province	Free-floating or attached to surfaces in water, or in soils.	-	Kalana *et al*., 2016
***Nannochloropsis* sp.**	Southern coast	Mostly found in marine *environment* but also occur in fresh and brackish water.	10.76%	Nagahawatta *et al*., 2015

***Oscillatoria* sp.**	Kandy	Salt marshes, salt pans	31.9%	Hossain *et al*., 2020, Bowange *et al.*, 2022
Sargassum sp.	Beruwala, Jaffna	Large, shallow pools on horizontal beachrock platforms, just above low water mark, continuously wave-swept	-	Coppejans *et al*., 2009, Fernando & Ranganathan, 2019
Scenedesmus sp.	Victoria reservoir, Central province and Ulhitiya reservoir, Uva province	Eutrophic freshwaters but rarely found in brackish water	-	Kalana *et al*., 2016

Macroalgae also present important opportunities for integrated biorefinery development. Brown seaweeds such as *Sargassum* and *Turbinaria*, together with green algae including *Ulva* and *Caulerpa*, can simultaneously serve as feedstocks for biofuel production and sources of commercially valuable products such as alginate, agar, pigments, antioxidants, and animal feed ingredients (Matos *et al*., 2021; Ferreira *et al*., 2022). Such multiproduct utilization has the potential to improve process economics while supporting circular bioeconomy principles.

Although comparatively fewer studies have investigated the biofuel potential of Sri Lankan macroalgae, the country possesses numerous native seaweed species with promising characteristics for future biodiesel and biocrude production. Table 2 presents macroalgal species reported from Sri Lankan coastal waters that have demonstrated favorable biofuel-related properties in studies conducted elsewhere. While these species have not yet been comprehensively evaluated under Sri Lankan conditions, international findings suggest considerable potential for future research and commercial development. Consequently, these species represent important candidates for expanding Sri Lanka's algal biorefinery research beyond the currently investigated microalgal species.

Table 2. Native Sri Lankan macroalgal species with reported biofuel potential based on international studies.

Algae Species	**Reported distribution in Sri Lanka**	**Ecology**	**Lipid content investigated in different countries**	**References**

			Yield	**Country**	
Dunaliella salina	Unawatuna	High salinity environments such as salted brines, salt evaporation ponds, and hypersaline lakes	16-44 %	United States	Coppejans *et al*., 2009, Weldy & Huesemann (n.d.)
Chaetomorpha antennina	Unawatuna	Epilithic in high intertidal, best developed on the seaward side of rocks along surf-exposed coasts	2.70 %	Ghana cost, Gunea	Coppejans *et al*., 2009, Ameka *et al*., 2019
***Jania* sp.**	Dickwella	Growing in large, rather dense, on vertical and sloping surfaces in the mid to low intertidal, exposed to extreme surf, forming extensive vegetations in the middle intertidal along surf-exposed coasts	1.56%	Egypt	Coppejans *et al*., 2009, Maghraby & Fakhry, 2014
Padina sp.	Beruwala	Shallow, rather sheltered low intertidal pools.	3.01%	Egypt	Coppejans *et al*., 2009, Maghraby & Fakhry, 2014
Ulva sp.	Talpe, Koggala	Epilithic in shallow intertidal pools	9.4-12.2%	Egypt	Premarathna *et al*., 2019, Coppejans *et al*., 2009, Moustafa & Batran, 2014
Ulva reticulata	Talpe	Entangled to other algae in the whole intertidal zone and shallow subtidal	19.98%	India	Premarathna *et al*., 2019, Coppejans *et al*., 2009, Shanmugam & Palpandi, 2008

Valoniopsis pachynema	Talpe, Koggala, Ahangama	Extremely abundant on beachrock platforms, just above low water mark.	82.33 mg/gm	India	Premarathna *et al.*, 2019, Coppejans *et al*., 2009, Roy & Anantharaman , 2017
Gracilaria folifera	Galle, Hikkaduwa	Epilithic, on surf-exposed rocks at about low tide level, extremely well-developed in surf channels	3.23%	India	Roy & Anantharaman , 2017, Coppejans *et al*., 2009
Sargassum wightii	Nilwella, Hikkaduwa	Epilithic on horizontal beachrock, surf-exposed margins just above low water; forms extensive vegetation; larger, slender growth on shallow subtidal walls	2.337%	India	Roy & Anantharaman , 2017, Coppejans *et al.*, 2009
Ulva lactuca	Hikkaduwa, Dickwella	Epilithic in shallow intertidal pools	1.6%	India	Roy & Anantharaman , 2017, Coppejans *et al*., 2009
Codium tomentosum	Southern coast, Trincomalee	Epilithic on horizontal substratum, also on vertical walls, shallow subtidal from low water to 50 cm depth; locally extremely abundant.	2.52%	India	Roy & Anantharaman , 2017, Coppejans *et al.*, 2009

Representative macroalgal species reported from Sri Lankan coastal waters are illustrated in Figure 1. The figure highlights the remarkable morphological diversity of native seaweed that have been documented across different coastal habitats of the island. Although only a limited number of these species have been investigated for biodiesel production under Sri Lankan conditions, several have demonstrated

promising biofuel potential in studies conducted elsewhere (Table 2). This diversity indicates that Sri Lanka possesses a broader algal resource base than is currently reflected in the national biofuel literature and provides opportunities for expanding future research beyond the relatively few indigenous species that have been experimentally evaluated to date. Consequently, systematic screening of these locally available macroalgae for biomass productivity, lipid composition, hydrothermal liquefaction performance, and integrated biorefinery applications could substantially strengthen the country's algal biofuel research portfolio (Premarathna *et al.*, 2020; Matos *et al*., 2021; Ferreira *et al*., 2022).



Figure 1: Representative macroalgal species reported from Sri Lankan coastal ecosystems with potential relevance for future biofuel and biorefinery applications.

SW01–SW23 represent: Ulva lactuca, *Caulerpa racemosa*, *Gracilaria corticata*, *Padina antillarum*, *Sargassum illicifolium*, *Sargassum polycystum*, *Halimeda opuntia*, *Caulerpa sertularioides*, *Turbinaria ornata*, *Stoechospermum polypodioides*, *Acanthophora spicifera*, *Gelidiopsis variabilis*, *Chaetomorpha antennina*, *Chaetomorpha crassa*, and *Jania adhaerens* (adapted from Premarathna *et al*., 2020).

2.4 Wastewater Resources and Industrial CO_2 Utilization

One of the most promising opportunities for reducing algal biodiesel production costs in Sri Lanka lies in integrating algal cultivation with wastewater treatment and industrial carbon capture. Municipal wastewater, aquaculture effluents, and agricultural and industrial wastewaters contain significant concentrations of nitrogen and phosphorus that can support rapid algal growth while simultaneously improving water quality (Nguyen *et al*., 2022; Dias *et al*., 2025).

Sri Lankan studies have demonstrated that indigenous microalgae isolated from wastewater environments exhibit high nutrient uptake efficiencies together with favorable biomass productivity (Thevarajah *et al*., 2024). Similarly, industrial CO_2 emissions from thermal power stations, cement manufacturing plants, and other industrial facilities could provide concentrated carbon sources for algal cultivation while contributing to greenhouse gas mitigation. Integrating wastewater treatment with CO_2 utilization would improve resource efficiency, reduce operational costs, and strengthen the environmental sustainability of future algal biorefineries.

2.5 Critical Assessment of Sri Lanka's Ecological Potential

The evidence reviewed above demonstrates that Sri Lanka possesses many of the natural characteristics considered favorable for algal biomass production, including suitable climatic conditions, diverse aquatic ecosystems, and a wide range of indigenous algal species with promising biodiesel potential. Nevertheless, ecological suitability should not be interpreted as evidence of commercial readiness. Similar environmental advantages exist in several countries that continue to experience significant barriers to large-scale algal biodiesel production, including high harvesting costs, energy-intensive downstream processing, and limited economic competitiveness relative to conventional fuels (Carneiro *et al*., 2017; Collet *et al*., 2014; Osman *et al*., 2024).

Consequently, Sri Lanka's greatest comparative advantage may lie not simply in its favorable climate or biodiversity but in its opportunity to integrate algal cultivation with wastewater treatment, industrial carbon capture, and multiproduct biorefineries that improve overall process economics. Future research should therefore move beyond species screening and laboratory-scale cultivation towards pilot-scale demonstration, techno-economic analysis, life-cycle assessment, and integrated

resource management. Such studies are essential to determine whether Sri Lanka's ecological potential can be translated into a commercially viable algal biodiesel industry.

3. Technological Readiness of Algal Biodiesel Production in Sri Lanka

3.1 Biodiesel Production Pathways

The conversion of algal biomass into biodiesel involves a series of interconnected processes, including biomass cultivation, harvesting, lipid extraction, and fuel conversion. The choice of conversion pathway depends on the biochemical composition of the algal biomass, moisture content, desired end products, and overall process economics. Among the available technologies, lipid extraction followed by transesterification remains the most widely investigated route for lipid-rich microalgae, whereas thermochemical processes such as hydrothermal liquefaction (HTL) have emerged as attractive alternatives for processing wet macroalgal biomass without energy-intensive drying (Mahmood *et al*., 2023; Venkatachalam *et al*., 2021).

Although these technologies have been extensively investigated worldwide, their level of development in Sri Lanka remains largely confined to laboratory-scale studies. Research has primarily focused on identifying suitable indigenous algal species, optimizing cultivation conditions, improving lipid extraction efficiency, and evaluating biodiesel quality. Consequently, the country's research efforts have established important scientific foundations, but further technological development is required before commercial-scale implementation can be achieved.

The overall process involved in converting algal biomass into biodiesel is illustrated in Figure 2. The figure highlights the sequential stages of biomass cultivation, harvesting, drying, lipid extraction, transesterification, and biodiesel purification. It also illustrates the key processing steps where technological improvements are most likely to enhance overall process efficiency and economic viability.

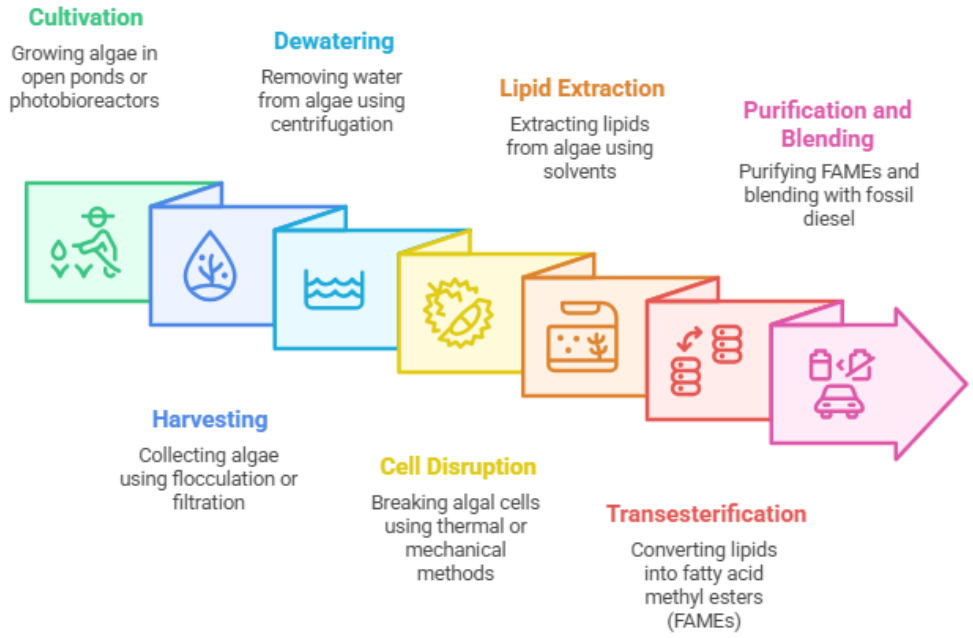


Figure 2: Basic processes involved in producing Algae Biodiesel

Among the available conversion routes, transesterification remains the preferred process for producing biodiesel from lipid-rich microalgae because of its relatively high conversion efficiency, established technology, and compatibility with existing diesel engines (Rashid & Hazmi, 2022). However, efficient biodiesel production depends not only on the conversion reaction itself but also on upstream processes such as biomass cultivation, harvesting, cell disruption, and lipid recovery, which collectively account for a substantial proportion of production costs (Collet *et al*., 2014; Osman *et al*., 2024). Consequently, recent research has increasingly focused on improving the efficiency of the entire production chain rather than optimizing transesterification alone.

Lipid extraction continues to play a critical role in determining biodiesel yield and quality. Conventional solvent extraction remains the most widely applied laboratory technique because of its high recovery efficiency, while mechanical disruption, microwave-assisted extraction, ultrasonic treatment, and supercritical fluid extraction have been investigated to improve extraction efficiency and reduce solvent consumption (Matos *et al*., 2021). Similarly, hydrothermal liquefaction has gained increasing attention as an alternative conversion technology for macroalgae because it enables direct processing of wet biomass into biocrude, thereby eliminating the

need for energy-intensive drying and reducing overall processing requirements (Biswas *et al*., 2018; Allen & Pearce, 2024).

Despite significant advances in individual processing technologies, harvesting, dewatering, lipid extraction, and downstream purification remain the major contributors to the overall production cost of algal biodiesel worldwide (Carneiro *et al*., 2017; Collet *et al*., 2014). These technological bottlenecks are equally relevant to Sri Lanka and highlight the importance of developing integrated production systems that combine wastewater treatment, industrial CO_2 utilization, and high-value co-product recovery to improve economic feasibility. Therefore, future technological development should focus not only on maximizing biodiesel yield but also on improving the efficiency and sustainability of the entire algal biorefinery process.

3.2 Current Research Achievements in Sri Lanka

Over the past decade, research on algal biodiesel in Sri Lanka has progressed from preliminary species identification to laboratory-scale investigations of biomass cultivation, lipid extraction, biodiesel production, and hydrothermal conversion. Although the overall research output remains relatively limited compared with leading countries in algal biotechnology, existing studies have demonstrated the feasibility of utilizing indigenous microalgal and macroalgal species as renewable feedstocks for biofuel production. The majority of these investigations have focused on optimizing cultivation conditions, improving lipid recovery, and evaluating fuel quality, thereby establishing an important scientific foundation for future technological development.

Among the indigenous microalgal species investigated, *Chlorella homosphaera*, *Desmodesmus* sp., *Scenedesmus* sp., *Oscillatoria* sp., and several cyanobacterial isolates have shown promising characteristics for biodiesel production. Sandani *et al*. (2020) demonstrated that appropriate pretreatment strategies significantly enhanced lipid recovery from locally isolated *Chlorella homosphaera*, resulting in improved biodiesel yield and fuel quality. Similarly, Premaratne *et al*. (2021) reported that nitrogen-limited cultivation of a locally isolated *Desmodesmus* sp. increased lipid accumulation while simultaneously enabling carbon dioxide sequestration from simulated cement flue gas, highlighting the dual environmental benefits of algal cultivation. In addition, Fuad Hossain *et al*. (2020) successfully isolated and cultured several cyanobacterial strains from Sri Lankan freshwater bodies and confirmed their potential as biodiesel feedstocks based on biomass productivity and lipid composition.

Sri Lankan research has also explored the utilization of marine macroalgae as alternative biofuel feedstocks. Although macroalgae generally contain lower lipid

contents than microalgae, their rapid biomass production, abundance along the Sri Lankan coastline, and suitability for hydrothermal liquefaction make them attractive candidates for integrated biorefinery applications. Biswas *et al*. (2018) demonstrated the successful conversion of *Sargassum tenerrimum* into biocrude using hydrothermal liquefaction, while Vimali *et al*. (2022) reported efficient fatty acid methyl ester production together with bio-oil generation from *Padina tetrastromatica*. These studies indicate that macroalgae could complement microalgal biodiesel production by providing alternative conversion pathways that reduce the need for energy-intensive drying.

Another notable strength of Sri Lankan research is the increasing integration of algal biotechnology with environmental remediation. Several studies have investigated the cultivation of indigenous algae using wastewater or industrial flue gas, demonstrating simultaneous nutrient removal, carbon dioxide sequestration, and biomass production (Premaratne *et al*., 2021; Thevarajah *et al.*, 2024). Such integrated approaches are particularly relevant for Sri Lanka because they have the potential to reduce cultivation costs while improving the overall environmental sustainability of algal biodiesel production. The combination of wastewater treatment, carbon capture, and biofuel production is consistent with circular bioeconomy principles and may provide greater economic viability than stand-alone biodiesel production.

The principal findings of published Sri Lankan studies investigating indigenous algal species for biodiesel production are summarized in Table 1 in section 2. Collectively, these investigations demonstrate that several locally available species possess favorable characteristics for biofuel production under laboratory conditions. However, most studies remain confined to controlled experimental environments, with limited evaluation of large-scale cultivation, continuous biomass production, downstream processing, or fuel economics.

Overall, the available evidence indicates that Sri Lanka has successfully established the scientific basis for algal biodiesel research through species isolation, cultivation studies, lipid extraction, and preliminary fuel characterization. Nevertheless, the current research landscape remains fragmented, with relatively few multidisciplinary investigations integrating cultivation, conversion technology, economic assessment, and environmental sustainability within a single production system. Consequently, although laboratory-scale achievements are encouraging, substantial research is still required before these technologies can be translated into pilot-scale demonstrations and ultimately commercial applications.

3.3 Technological Readiness of Algal Biodiesel Production in Sri Lanka

Although Sri Lanka has made encouraging progress in identifying indigenous algal species suitable for biodiesel production and optimizing laboratory-scale cultivation and lipid extraction techniques, the overall technological maturity of the sector remains relatively low. Evaluating the current status using the Technology Readiness Level (TRL) framework provides a useful means of assessing the transition from fundamental research to commercial deployment. The TRL framework, originally developed for technology assessment, has been widely adopted to evaluate the maturity of emerging renewable energy technologies by categorizing development from basic scientific research (TRL 1) to fully operational commercial systems (TRL 9).

Current evidence suggests that most algal biodiesel research conducted in Sri Lanka falls within TRL 3–4, where experimental proof-of-concept has been established under controlled laboratory conditions. Studies have successfully demonstrated the isolation and cultivation of indigenous microalgae, optimization of lipid extraction methods, biodiesel production through transesterification, and preliminary fuel quality evaluation (Sandani *et al*., 2020; Fuad Hossain *et al*., 2020; Premaratne *et al*., 2021). Similarly, investigations on macroalgae have demonstrated the feasibility of hydrothermal liquefaction and bio-oil production using selected marine species (Biswas *et al*., 2018; Vimali *et al*., 2022). These achievements confirm the scientific feasibility of algal biofuel production under laboratory conditions.

However, the transition beyond laboratory-scale validation has been limited. At present, there are no published reports of pilot-scale cultivation facilities, continuous biomass production systems, integrated biorefineries, or commercial demonstration plants dedicated to algal biodiesel production in Sri Lanka. Furthermore, comprehensive techno-economic analyses, life-cycle assessments, supply chain optimization, and commercial feasibility studies remain scarce. Similar limitations have been reported internationally, where technological feasibility has not always translated into economic viability because of high harvesting costs, energy-intensive downstream processing, and substantial capital investment requirements (Collet *et al*., 2014; Carneiro *et al.*, 2017; Osman *et al*., 2024). Consequently, Sri Lanka's current research status closely reflects the global trend, where scientific advances have generally progressed faster than commercial implementation.

Moving towards higher technology readiness levels will require coordinated multidisciplinary research extending beyond laboratory optimization. Priority should be given to establishing pilot-scale cultivation systems capable of operating under local climatic conditions, integrating algal cultivation with municipal and industrial wastewater treatment, evaluating industrial carbon dioxide utilization, and

developing scalable harvesting and dewatering technologies. Equally important are comprehensive techno-economic assessments and life-cycle analyses that quantify the economic competitiveness and environmental performance of proposed production systems under Sri Lankan conditions. Such studies will provide the evidence required to support industrial investment and policy formulation.

Overall, Sri Lanka has successfully established the scientific foundation for algal biodiesel production; however, the technology has not yet progressed beyond laboratory validation. Advancing from TRL 3–4 towards pilot-scale demonstration (TRL 5–6) represents the most critical next step for transforming promising laboratory research into commercially relevant technology. Therefore, future research should priorities integrated demonstration projects that simultaneously evaluate technical performance, economic feasibility, and environmental sustainability, thereby providing a realistic pathway towards commercial implementation.

4. Sustainability Benefits and Circular Bioeconomy Opportunities of Algal Biodiesel

Algal biodiesel offers several environmental and socio-economic advantages over conventional fossil fuels and first-generation biodiesel feedstocks. Unlike edible oil crops, microalgae and macroalgae can be cultivated on non-arable land using freshwater, brackish water, seawater, or wastewater, thereby avoiding direct competition with food production and reducing pressure on agricultural land resources (Mahmood *et al*., 2023; Purnama *et al*., 2025). Furthermore, the rapid growth rates, high photosynthetic efficiency, and ability to accumulate substantial quantities of lipids make algae an attractive renewable feedstock for sustainable biofuel production. However, the sustainability of algal biodiesel should not be evaluated solely on fuel production but rather through its contribution to integrated resource recovery, environmental protection, and circular bioeconomy development.

4.1 Environmental Benefits of Algal Biodiesel

One of the principal environmental advantages of algae-based biofuels is their capacity to simultaneously capture atmospheric or industrial carbon dioxide while producing renewable biomass. During photosynthesis, microalgae efficiently assimilate CO_2, contributing to greenhouse gas mitigation and partially offsetting emissions associated with fuel production (Ighalo *et al.*, 2022; Sadvakasova *et al*., 2025). In addition, algae can remove excess nitrogen and phosphorus from municipal, agricultural, and industrial wastewater, thereby reducing eutrophication while generating valuable biomass suitable for biofuel production (Nguyen *et al*., 2022; Dias *et al*., 2025). This dual function distinguishes algal cultivation from

conventional biofuel production systems and strengthens its environmental sustainability.

Compared with fossil diesel, biodiesel derived from algae contains negligible Sulphur, produces lower particulate emissions, and has the potential to reduce net greenhouse gas emissions when cultivation and processing are appropriately integrated (Woertz *et al*., 2014). Nevertheless, recent life-cycle assessments indicate that these environmental benefits depend strongly on cultivation methods, harvesting technologies, energy inputs, and the utilization of co-products (Carneiro *et al*., 2017; Collet *et al*., 2014). Consequently, environmental sustainability cannot be assumed solely on the basis of using algal biomass as a feedstock but must be evaluated across the entire production system.

4.2 Contribution to the Circular Bioeconomy

The concept of a circular bioeconomy seeks to maximize resource utilization while minimizing waste generation through integrated production systems. Algal biorefineries are well aligned with this concept because they enable the simultaneous production of biodiesel together with high-value products such as pigments, antioxidants, proteins, polysaccharides, animal feed ingredients, fertilizers, and biochar (Matos *et al*., 2021; Ferreira *et al*., 2022). Revenue generated from these co-products can substantially improve the overall economics of algal biodiesel production, addressing one of the major barriers to commercialization.

Sri Lanka offers several opportunities for implementing circular bioeconomy strategies through the integration of algal cultivation with existing industrial and environmental infrastructure. Municipal wastewater treatment facilities, aquaculture operations, food processing industries, and cement manufacturing plants provide potential sources of nutrients and carbon dioxide that could support algal cultivation while simultaneously reducing environmental pollution (Premaratne *et al*., 2021; Thevarajah *et al*., 2024). Such integrated systems would reduce cultivation costs, improve resource efficiency, and enhance the environmental performance of future algal biorefineries.

The comparative sustainability characteristics of algae and conventional biodiesel feedstocks are summarised in Table 3. Compared with coconut, palm oil, and sugarcane, algae offer several important advantages, including substantially higher oil productivity, the ability to utilize non-arable land and wastewater, greater carbon sequestration potential, and opportunities for integrated biorefinery development. These characteristics make algal biomass particularly attractive for Sri Lanka, where agricultural land and freshwater resources are increasingly constrained.

Table 3. Sustainability comparison of algae and conventional biodiesel feedstocks relevant to Sri Lanka.

Parameter	**Algae**	**Coconut**	**Palm oil**	**Sugarcane**
Land requirement	Very low (non-arable land possible)	High	High	Moderate
Freshwater requirement	Low–Moderate (wastewater can be used)	High	High	High
Food competition	None	Yes	Yes	Partial
Oil yield (L ha^{-1} yr^{-1})	20,000–40,000	~1,500	~6,000	N/A
CO_2 sequestration	Very high	Low	Moderate	Low
Wastewater utilization	Excellent	Poor	Poor	Limited
Cultivation in saline water	Yes	No	No	No
Biodiversity impact	Low (if managed sustainably)	Moderate	High	Moderate
Potential for biorefinery products	Very high	Moderate	Moderate	Low

4.3 Contribution Towards Sustainable Development Goals

The development of an algal biodiesel industry has the potential to contribute directly to several United Nations Sustainable Development Goals (SDGs). Renewable biofuel production supports SDG 7 (Affordable and Clean Energy) by promoting alternative energy sources that reduce dependence on imported fossil fuels. The ability of algae to capture carbon dioxide contributes to SDG 13 (Climate Action), while wastewater-based cultivation supports SDG 6 (Clean Water and Sanitation) through nutrient removal and water quality improvement. Furthermore, integrated algal biorefineries encourage responsible resource utilization, contributing to SDG 12 (Responsible Consumption and Production), and may create new employment opportunities within the emerging bioeconomy, supporting SDG 8 (Decent Work and Economic Growth).

For Sri Lanka, these contributions are particularly relevant because the country faces increasing challenges related to energy security, climate resilience, wastewater management, and sustainable industrial development. Consequently, algal biodiesel should be considered not merely as an alternative fuel but as part of a broader environmental management strategy that simultaneously addresses multiple national sustainability objectives.

4.4 Critical Perspective on Sustainability

Although algal biodiesel is frequently described as one of the most sustainable biofuel options, its overall environmental performance depends on the efficiency of the entire production chain. Numerous international studies have shown that energy-intensive harvesting, dewatering, drying, and downstream processing can substantially increase production costs and environmental impacts, particularly when powered by fossil-based electricity (Collet *et al*., 2014; Carneiro *et al*., 2017). Consequently, the sustainability advantages of algal biodiesel can only be fully realized when production systems are integrated with wastewater treatment, industrial carbon capture, renewable energy sources, and high-value co-product recovery.

For Sri Lanka, the greatest opportunity lies not in competing with conventional petroleum fuels solely on biodiesel production but in developing integrated algal biorefineries that simultaneously produce renewable fuels, recover valuable resources, and provide environmental services. Such an approach would improve economic resilience while maximizing the environmental benefits of the country's rich algal biodiversity. Therefore, future research should increasingly focus on system-level optimization rather than isolated improvements in biomass productivity or lipid yield.

5. Can Sri Lanka Commercialize Algal Biodiesel? Lessons from International Experience

The successful commercialization of algal biodiesel depends not only on favorable environmental conditions but also on technological maturity, economic viability, supportive policy frameworks, and industrial investment. Although Sri Lanka possesses several natural advantages for algal cultivation, including abundant solar radiation, favorable climatic conditions, rich aquatic biodiversity, and extensive coastal resources as shown in Figure 3, these characteristics alone do not guarantee successful commercial implementation. Experiences from countries that have invested substantially in algal biotechnology demonstrate that significant challenges remain despite decades of scientific research. Therefore, evaluating Sri Lanka's future prospects requires consideration of both national strengths and the lessons learned from international commercialization efforts.

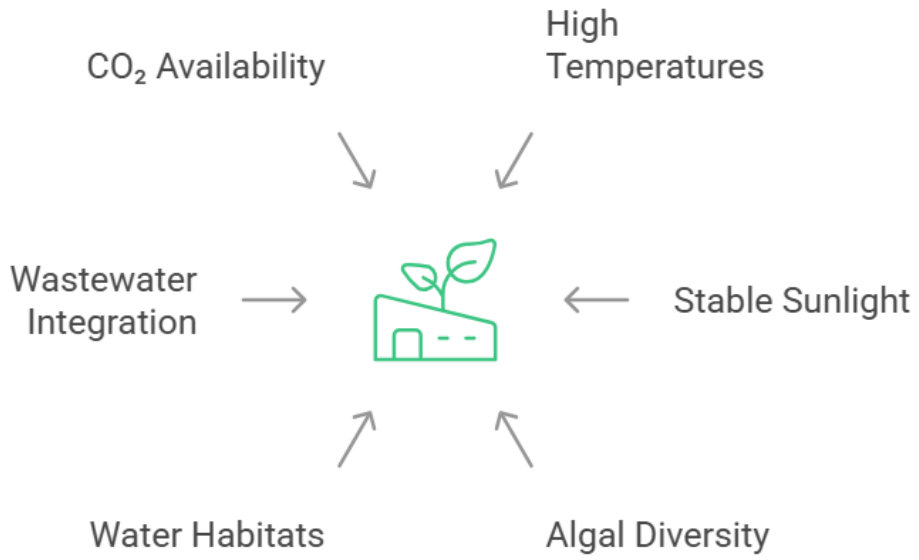


Figure 3: Factors supporting Algae biomass production in Sri Lanka

5.1 Lessons from International Commercialization

Over the past two decades, countries including the United States, China, Australia, India, Japan, and several European nations have invested heavily in algal biofuel research. These investments have resulted in considerable advances in algal cultivation, strain improvement, harvesting technologies, lipid extraction, and biorefinery development. Nevertheless, commercial-scale biodiesel production remains limited because the overall production cost continues to exceed that of petroleum diesel and many first-generation biofuels (Collet *et al*., 2014; Carneiro *et al*., 2017; Osman *et al*., 2024).

One of the principal reasons for this slow commercialization is the high energy demand associated with harvesting, dewatering, drying, and downstream processing. Since microalgae are typically cultivated in dilute aqueous suspensions, biomass recovery often accounts for a substantial proportion of total production costs. Furthermore, maintaining stable large-scale cultivation systems while preventing contamination and ensuring consistent biomass productivity remains technically challenging. These limitations have encouraged increasing interest in integrated biorefineries, where biodiesel production is combined with the recovery of high-value products such as pigments, nutraceuticals, animal feed, biofertilizers, and specialty

chemicals to improve overall economic viability (Matos *et al*., 2021; Ferreira *et al*., 2022).

International experience also demonstrates that successful commercialization depends on strong collaboration among universities, government agencies, and industry. Countries that have progressed beyond laboratory research have generally benefited from sustained research funding, pilot-scale demonstration facilities, supportive renewable energy policies, and active industrial participation. These experiences provide valuable guidance for Sri Lanka, where similar multidisciplinary collaborations will be essential for translating laboratory-scale achievements into commercially viable technologies.

5.2 Technological Challenges

Although laboratory-scale studies conducted in Sri Lanka have demonstrated the feasibility of producing biodiesel from indigenous algal species, several technological challenges continue to limit commercial development. Biomass harvesting and dewatering remain particularly energy-intensive because algal cultures generally contain low biomass concentrations, requiring efficient separation technologies before lipid extraction can be performed (Collet *et al*., 2014). In addition, variations in lipid productivity caused by environmental conditions, nutrient availability, and species-specific characteristics make process optimization more complex than conventional agricultural feedstocks.

The absence of pilot-scale cultivation facilities further limits opportunities to evaluate operational performance under realistic environmental conditions. Consequently, important factors such as long-term biomass productivity, contamination control, seasonal variation, process integration, and continuous operation remain largely unexplored in Sri Lanka. Addressing these challenges will require interdisciplinary collaboration involving microbiologists, chemical engineers, environmental scientists, and industrial partners to develop scalable cultivation and processing technologies.

5.3 Economic Challenges

Economic feasibility remains the greatest obstacle to commercial algal biodiesel production worldwide. Although algae exhibit exceptionally high theoretical oil productivity, production costs remain significantly higher than those of conventional diesel because of cultivation infrastructure, harvesting, drying, lipid extraction, and downstream processing requirements (Carneiro *et al*., 2017; Osman *et al*., 2024). Similar economic constraints are likely to affect Sri Lanka unless production systems are designed to maximize resource efficiency and generate multiple revenue streams.

The integration of algal cultivation with wastewater treatment, industrial carbon dioxide utilization, and the recovery of high-value co-products provides promising opportunities for improving economic viability. Rather than relying solely on biodiesel sales, future Sri Lankan biorefineries should adopt integrated production models in which biodiesel is one component of a broader portfolio including pigments, antioxidants, proteins, biofertilizers, and other commercially valuable products. Such diversified production systems are increasingly recognized as the most realistic pathway towards commercial sustainability.

5.4 Policy and Institutional Challenges

Technological advances alone are insufficient to establish a successful algal biodiesel industry. Appropriate policy frameworks, research funding mechanisms, regulatory support, and industrial incentives are equally important for encouraging investment and facilitating technology transfer. At present, Sri Lanka lacks a dedicated national strategy for algal biofuel development, and research activities remain largely confined to universities and research institutions.

Future policy initiatives should promote pilot-scale demonstration projects, strengthen collaboration between academia and industry, encourage private-sector investment, and integrate algal biotechnology into broader national strategies on renewable energy, climate change mitigation, wastewater management, and the circular bioeconomy. Establishing such an enabling policy environment would substantially improve the prospects for commercial deployment.

5.5 Critical Assessment: Is Sri Lanka Ready for Commercialization?

The evidence reviewed throughout this paper suggests that Sri Lanka possesses many of the natural and scientific prerequisites required for developing an algal biodiesel industry, including favorable climatic conditions, diverse indigenous algal resources, and a growing body of laboratory-scale research. However, these strengths alone are insufficient to achieve commercial success. International experience consistently demonstrates that the transition from laboratory research to industrial production depends on overcoming technological bottlenecks, demonstrating economic competitiveness, and establishing supportive policy and investment frameworks.

Consequently, Sri Lanka should not attempt to replicate conventional stand-alone biodiesel production models. Instead, greater emphasis should be placed on developing integrated algal biorefineries that combine renewable fuel production with wastewater treatment, carbon dioxide sequestration, and the recovery of high-value bioproducts. Such an approach would improve both environmental sustainability and economic resilience while taking advantage of the country's existing natural resources. Therefore, although Sri Lanka is not yet ready for large-

scale commercialization, it possesses considerable potential to become a regional leader in sustainable algal biotechnology if future research, industrial investment, and national policy development progress in a coordinated manner.

6. Future Research Priorities and Conclusions

6.1 Future Research Priorities

The findings presented throughout this review demonstrate that Sri Lanka possesses favorable climatic conditions, diverse indigenous algal resources, and an emerging scientific foundation for algal biodiesel production. Nevertheless, the transition from laboratory-scale research to commercial implementation will require coordinated advances across multiple scientific, technological, economic, and policy domains. Consequently, future research should focus on addressing the critical knowledge gaps that currently limit large-scale deployment.

One of the highest priorities is the establishment of pilot-scale cultivation and demonstration facilities capable of evaluating algal biomass production under realistic environmental conditions. While laboratory investigations have confirmed the biodiesel potential of several indigenous microalgal and macroalgal species, pilot-scale studies are essential to assess long-term productivity, contamination control, harvesting efficiency, and seasonal variability. Such facilities would also provide valuable information on operational costs and process optimization under Sri Lankan conditions.

Future investigations should also place greater emphasis on integrated algal biorefineries rather than biodiesel production alone. International experience has demonstrated that commercial viability is significantly enhanced when biodiesel production is combined with wastewater treatment, industrial carbon dioxide utilization, and the recovery of high-value co-products such as pigments, antioxidants, proteins, biofertilizers, and specialty chemicals (Matos *et al*., 2021; Ferreira *et al*., 2022). This integrated approach is particularly relevant to Sri Lanka because it simultaneously addresses renewable energy production, environmental protection, and resource recovery within a circular bioeconomy framework.

Another important research priority is the application of techno-economic assessment (TEA) and life-cycle assessment (LCA) to proposed algal biodiesel production systems. Although laboratory-scale investigations have demonstrated technical feasibility, comprehensive assessments of economic competitiveness, environmental impacts, and overall sustainability remain scarce in Sri Lanka. Such analyses are essential for identifying cost drivers, evaluating greenhouse gas mitigation potential, and supporting evidence-based investment and policy decisions.

Finally, greater collaboration between universities, government agencies, research institutions, and industry will be necessary to accelerate technology transfer and commercialization. National research programs should encourage multidisciplinary projects involving microbiology, biotechnology, environmental science, chemical engineering, and industrial process design while promoting partnerships with wastewater treatment facilities, aquaculture operations, and manufacturing industries. Such collaborative initiatives would strengthen Sri Lanka's capacity to develop a sustainable algal biotechnology sector while supporting national renewable energy and climate change mitigation strategies.

6.2 Conclusions

Algal biodiesel represents one of the most promising third-generation biofuel technologies because of its high biomass productivity, efficient carbon dioxide sequestration, and ability to utilize non-arable land, saline water, and wastewater resources. This review demonstrates that Sri Lanka possesses several natural advantages supporting algal biomass production, including favorable climatic conditions, extensive freshwater and coastal ecosystems, and a diverse range of indigenous microalgal and macroalgal species with demonstrated biofuel potential. Laboratory-scale investigations have successfully established the scientific feasibility of biodiesel production from several locally available species, providing a valuable foundation for future technological development.

However, evidence from both Sri Lanka and international experience indicates that favorable ecological conditions alone are insufficient for successful commercialization. Significant challenges remain in harvesting, downstream processing, economic competitiveness, policy support, and technology scale-up. The current level of technological development in Sri Lanka is largely confined to laboratory validation, highlighting the need for pilot-scale demonstration projects, integrated biorefineries, and comprehensive techno-economic and life-cycle assessments before commercial implementation can be realized.

Rather than pursuing stand-alone biodiesel production, Sri Lanka has the opportunity to develop an integrated algal bioeconomy that combines renewable fuel production with wastewater treatment, industrial carbon dioxide utilization, and the recovery of high-value bioproducts. Such an approach would improve both environmental sustainability and economic resilience while contributing to national energy security and climate change mitigation. If supported by sustained scientific research, multidisciplinary collaboration, industrial investment, and enabling policy frameworks, Sri Lanka is well positioned to become a regional leader in sustainable algal biotechnology and a potential hub for integrated algal biorefinery development.

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