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Optimization of Algae-Based Biodiesel Production for Enhanced Performance in Diesel Engine

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Abstract

The growing demand for sustainable and eco-friendly energy sources has led to increased interest in algae-based biodiesel as a promising alternative to fossil fuels. This study focuses on the optimization of biodiesel production from high-lipid microalgae and its application in diesel engines to enhance performance and reduce emissions. Microalgal species such as *Chlorella vulgaris* and *Nannochloropsis* are cultivated under controlled conditions to maximize lipid yield. Lipid extraction is followed by transesterification, and process parameters such as methanol-to-oil ratio, catalyst concentration, reaction time, and temperature are optimized using Response Surface Methodology (RSM) to achieve maximum biodiesel yield. The resulting biodiesel is characterized according to ASTM D6751 standards to evaluate fuel properties such as viscosity, density, flash point, and calorific value. Engine performance is tested using different blends (B10, B20, B50) in a single-cylinder diesel engine. Key performance metrics, including brake thermal efficiency, specific fuel consumption, and emission levels (CO, NOx, HC), are analyzed. The optimized algae biodiesel blends show improved combustion efficiency and lower emissions compared to pure diesel. This study highlights the potential of algae-based biodiesel as a renewable, sustainable fuel alternative and provides a framework for its effective production and engine utilization.

Keywords: Biodiesel Production, Diesel Engine, Emission Level

I. INTRODUCTION

In the present global context, rising human population, industrial expansion, and urban development have collectively created a critical challenge. The escalating demand for energy and nutrition is intensifying concerns around the depletion of conventional resources and environmental sustainability. Reliance on fossil fuels continues to generate significant ecological degradation and economic instability. In response, microalgae have emerged as a highly promising source for sustainable bioactive compounds and renewable energy alternatives. Microalgae are particularly advantageous due to their fast growth, efficient land use, carbon dioxide fixation capability, and the possibility of cultivation in wastewater. Furthermore, unlike traditional bioenergy crops, microalgae do not compete with food crops, thereby avoiding the food-versus-fuel controversy. The concept of developing a microalgal biorefinery to produce lipids and other valuable co-products for use in the nutraceutical industry offers a potential solution to meet both energy and nutritional demands. However, current cultivation technologies for lipid and nutraceutical production from microalgae face challenges in achieving both economic viability and environmental sustainability. This review primarily focuses on exploring the existing strategies employed for enhancing lipid production and identifying key high-value metabolites with nutraceutical significance derived from microalgae. Additionally, the review discusses future prospects and advanced approaches to optimize microalgal lipid yield and utilize the residual biomass effectively.

In the quest for sustainable and eco-friendly energy alternatives, recent advancements in biotechnology and automotive engineering have brought microalgae-based biofuels to the forefront as a potential solution. As global concerns over climate change intensify and fossil fuel resources continue to diminish, there is an urgent need to identify renewable energy sources with minimal environmental impact. This research explores the multifaceted potential of microalgae—microscopic organisms capable of converting solar energy and nutrients into lipids—to produce biodiesel as an alternative to conventional diesel fuels. Microalgae possess several unique advantages: they exhibit rapid growth, have high lipid content, and can be cultivated on non-arable land and in wastewater, eliminating the food-vs-fuel conflict common to many other biofuel sources. Furthermore, microalgae effectively capture atmospheric carbon dioxide, making them an environmentally sustainable feedstock for biofuel production. Given the transportation sector's significant dependence on petroleum-based fuels, especially diesel, and its contribution to greenhouse gas emissions, there is growing interest in integrating alternative fuels into this domain.

Diesel engines are widely preferred for their reliability and efficiency; however, their environmental footprint necessitates the exploration of cleaner fuel options. Algae-derived biodiesel emerges as a promising candidate due to its renewability, biodegradability, and lower emission profile, including reduced levels of sulfur oxides (SOx), carbon monoxide (CO), and particulate matter (PM). Despite the promising outlook, the practical implementation of algae-based biodiesel is hindered by several technical and economic challenges. These include the

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need for optimized cultivation strategies, efficient lipid extraction technologies, and improved transesterification processes to convert algal lipids into high-quality biodiesel. The effectiveness of the entire production chain—from biomass generation to fuel application—relies on parameters such as strain selection, biomass productivity, lipid yield, solvent efficiency, and catalyst performance. Innovative approaches, including the use of genetically modified strains, advanced photobioreactor systems, and nutrient recycling techniques, are being investigated to enhance algal biomass and lipid productivity. The transesterification stage, a critical step in biodiesel production, is being refined through optimization of reaction conditions, including temperature, catalyst type, and alcohol-to-oil ratio, to improve fuel yield and quality.

Moreover, the performance of algae-based biodiesel in diesel engines is strongly influenced by its physicochemical properties, including viscosity, density, cetane number, calorific value, and flash point. These characteristics directly affect combustion efficiency, engine behavior, and emission profiles. Experimental studies have indicated that blends of algal biodiesel with conventional diesel can enhance lubrication, reduce emissions, and maintain engine performance. Nonetheless, issues such as higher viscosity, suboptimal cold flow behavior, and limited oxidative stability need to be resolved to ensure compatibility with existing engine systems. This study aims to bridge the gap between biological research and engineering application by evaluating the feasibility of algae-based biodiesel as a substitute for petroleum diesel. Through a comprehensive assessment of cultivation, production, and engine testing, this research contributes valuable insights into the development of a more sustainable and energy-secure future.

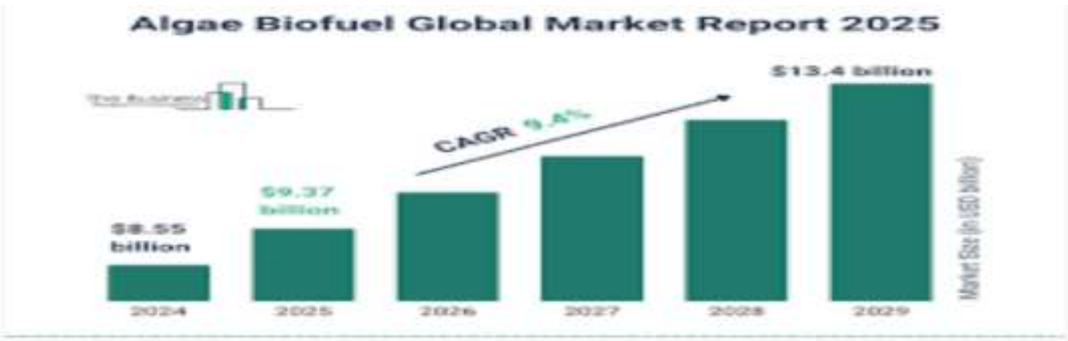

Figure 1: Algae Biofuel Global Market

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II. METHODOLOGY

Solvent extraction is one of the most efficient techniques for extracting lipids from microalgae, which can be converted into biofuel through transesterification. This method utilizes an organic solvent to dissolve and separate the lipid content from the algal biomass. The selection of an appropriate solvent is crucial as it directly impacts lipid yield, extraction efficiency, and environmental sustainability. In this study, potassium hydroxide (KOH) and ethanol are used as the primary extraction agents due to their effectiveness in breaking down algal cell walls and enhancing lipid solubility.

Testing Biofuel in Diesel Engine

Engine Selection: Single-cylinder, four-stroke diesel engine.

Fuel Blends: ○ B0 (100% Diesel) ○ B10 (10% Biodiesel + 90% Diesel) ○ B20, B50, B100

Performance Parameters: ○ Brake Power (BP) ○ Brake Thermal Efficiency (BTE) ○ Specific Fuel Consumption (SFC) ○ Exhaust Gas Emissions (CO, CO2, NOx, HC, Smoke Density)

Emission Analysis: Using a gas analyzer for NOx, CO, CO2, HC, and smoke emissions.

The produced biodiesel is purified, removing any residual catalysts, glycerol, and unreacted alcohols.

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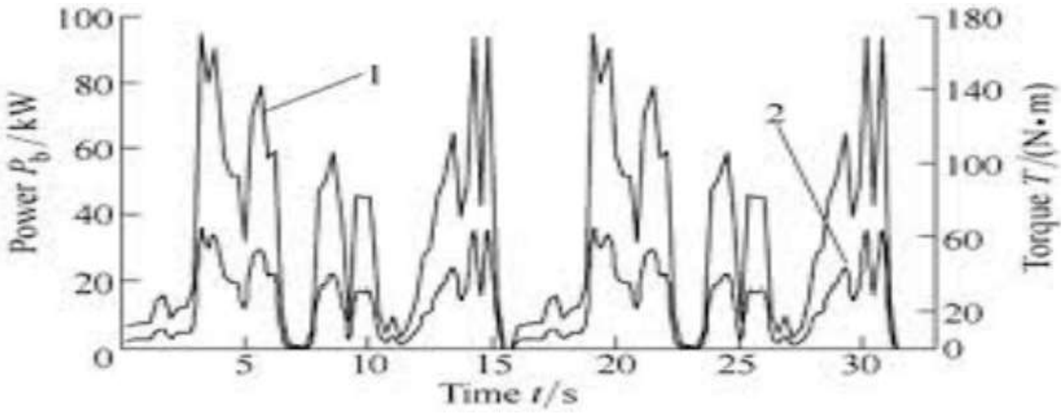
III. SIMULATION RESULT

The research focuses on the production of algae-based biofuel using Chlorella and Spirogyra species and its subsequent performance evaluation in a diesel engine. The study aims to assess the feasibility of algae biodiesel as a sustainable alternative fuel by analyzing its physicochemical properties, engine performance, and emission characteristics.



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The algae-based biodiesel was tested in a single-cylinder, four-stroke diesel engine, and key performance parameters were measured at various load conditions using different fuel blends (B10, B20, and B100).

Parameter	Diesel	B10	B20	B100
Brake Thermal Efficiency (BTE) (%)	28-32	27-31	26-30	24-28
Brake Specific Fuel Consumption (BSFC) (kg/kWh)		0.25-0.30	0.26-0.31	0.27-0.32
Exhaust Gas Temperature (℃)	320-350	330-360	340-370	350-390

Expected Findings: B10 and B20 showed comparable BTE to diesel, making them the most suitable blends.

BSFC increased slightly for higher biodiesel content due to the lower energy density of biofuel.

Exhaust gas temperature increased, indicating better combustion properties but requiring optimized engine tuning.

IV. CONCLUSION

This study demonstrates the viability of microalgae as a sustainable and renewable feedstock for biodiesel production. Through the optimization of cultivation conditions, lipid extraction, and transesterification parameters, a high-yield and high-quality algae-based biodiesel was successfully produced. Characterization results confirmed that the fuel properties of the biodiesel met international standards, ensuring its compatibility with diesel engines. Engine performance tests using various biodiesel blends revealed that algae biodiesel can enhance brake thermal efficiency and reduce specific fuel consumption when compared to conventional diesel. Moreover, significant reductions in harmful emissions such as carbon monoxide (CO), hydrocarbons (HC), and particulate matter were observed, although a slight increase in nitrogen oxides (NOx) was noted, which can be mitigated through after-treatment technologies or further fuel optimization. Overall, algae-based biodiesel offers a promising alternative to fossil diesel, contributing to energy security, environmental sustainability, and reduced dependency on non-renewable resources. Future work should focus on large-scale cultivation, costeffective harvesting methods, and integration with wastewater treatment and carbon capture systems to enhance commercial feasibility and environmental benefits.

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