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Algal Biodiesel for Energy Security: Societal, Policy, and Engineering Perspectives with RCCI Engine Applications

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Abstract
This article is a review-based study examining the role of algae derived biodiesel as a renewable energy source for improved energy security. Furthermore, it will investigate the impact that producing and using algae algae biodiesel have on society, policy and technology. In addition, this paper describes algae, as a feedstock with a high yield potential to help reduce society's dependency on fossil fuels and decrease greenhouse gas emissions. The engineering challenges that must be overcome to produce algae biodiesel through cultivation, harvest and extraction, are identified. The use of policy instruments, including incentives and regulations, to promote and incentivise the use of algae biodiesel, along with the benefits of algae biodiesel to society including economic development and environmental sustainability, are evaluated. A major focus will also be given to using algae biodiesel in reactivity controlled compression ignition (RCCI) engine technology and how improvements to combustion efficiency and emission reductions have been demonstrated in this area. The final section provides direction for future research efforts and highlights the important contribution algae biodiesel can make to achieving both sustainable transportation and long-term energy security
Keywords: algal Biodiesel, Energy Security, Societal Perspectives, Policy Frameworks, Engineering Innovations, RCCI Engines, Renewable Energy, Sustainable Transportation, Greenhouse Gas Reduction, Algae Cultivation

1. Introduction

1.1. **Background and Rationale:** The world energy demand is increasing at an alarming rate due to the high rates of industrialisation, population increase, and urbanisation, which makes it imperative to find a solution to the problem of sustainable and safe energy sources. Use of fossil fuel does not only threaten the economy by the risk of resources depletion but also exposes economies to geopolitical and price fluctuations, which pose vulnerabilities that jeopardize the energy security and environmental stability. Algal bio-diesel has in turn come out as a very attractive renewable biofuel due to its extremely high biomass productivity, high growth rate as well as the ability to effectively sequester carbon dioxide. Notably, there is no competition of algae growing with food crops or arable land, and the issue of food security and land-use strain is resolved. These properties make algal bio-diesel a good alternative to fossil based transport fuel and the environmental advantages are immense [1], [2], [3]. The advancement of engine technologies has led to the development of reactivity controlled compression ignition (RCCI) engines utilizing dual fuel combustion techniques for higher thermodynamic efficiency and lower/no emissions. An essential part of combustion control with RCCI is how the reactivity gradient in the combustion chamber is maintained through the mixing of fuels with different levels of reactivity (examples: biodiesel and petroleum-based fuels). This type of engine has significantly less nitrogen oxides (NOx) and particulate emissions than conventional compression ignition engines, and higher fuel economy than conventional compression ignitions as well. Additionally, RCCIs can also run on biodiesel blends which allows them to serve as a platform for the advancement of renewable fuels such as algae oils as fuels [4],[5],[6]. The relationship between algal biodiesel and RCCI technology has a great potential in the development of cleaner and efficient energy systems. The advantages of algal biodiesel include its renewable and carbon-neutral character, which is coupled with the high level of combustion of RCCI engines, and which together can help decrease greenhouse emissions and the local air pollution. This combined strategy considers the fuel supply and engine performance features that are main requirements towards sustainable transportation, making algal biodiesel-powered RCCI engines a direction on energy security, environmental sustainability, and decarbonization of transportation. Therefore, the utilization of algal biodiesel in RCCI engine design is a beneficial convergence of biofuel development and engine development to satisfy the urgent energy needs of the sustainable energy era [1], [2], [4].

1.2. Objectives of the study

The purpose of this review is to provide a complex assessment of the present situation and future opportunities of algae-based biodiesel in an interdisciplinary approach, focusing on technological, social, and policy factors. The targeted goals are as follows:

- To get a glimpse of the progress in yield, fuel quality and environmental sustainability, a systematic review of recent technological developments in algal biodiesel production which include cultivation methods, lipid extraction methods, genetic engineering and new methods such as nanofluid additives and integration into the circular economy has been carried out [1], [2], [7].
- The contribution of algal biodiesel to the improvement of energy security was assessed through the diversification of the energy sources, lessening reliance on fossil fuels, and subsidizing the local and global energy independence initiatives in the environment of rising energy demands and climate needs [1], [8].
- Acceptance, perceptions, and regulatory frameworks of adopting algal biodiesel in the society, such as environmental policies, emission laws, and economic incentives influencing market penetration and acceptance by the people have been examined [1], [9].

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- The issues and innovations in the field of engineering in regards to the integration of the algal biodiesel with Reactivity Controlled Compression Ignition (RCCI) engines are noted, with emphasis on the combustion performance, emission reduction, novel fuel blending approaches, injection methods, and new advanced improvements that include hydrogen enrichment and nanomaterials [4], [7], [10].
- Place the study in the context of other engineering and energy policy discussions, but with a particular focus on how technological innovation, environmental sustainability, and policy actions have to interact to facilitate a transition to cleaner, more efficient, and resilient energy systems [1], [11].

All these goals are intended to offer a comprehensive insight into the potential of algal biodiesel as a sustainable biofuel and how it can be combined with advanced engine technologies to inform future research, innovation, and policymaking in sustainable energy transitions.

2. Energy Security and Independence

2.1. **Role of Algal Biodiesel:** Algal biodiesel has great potential in the diversification of energy sources and lessening the dependence on fossil fuel imports, which is of paramount importance in strengthening the energy security and independence. The algae provide high lipid productivity with high rates of biomass production as opposed to the traditional sources of biofuels, which usually compete with food crops and need wide arable land, thus providing a scalable and sustainable source of energy. Research has revealed that algal biodiesel has the capability of producing lipid content up to 75 percent of dry biomass and up to 90 percent lower emissions of greenhouse gases than fossil diesel, which makes it an environmentally friendly alternative with a high economic potential in the renewable fuels industry [1], [2]. The concept of algae as fast growing organisms and the year-round generation of biomass facilitates the emergence of localised production systems. This decentralisation helps to counter the supply chain weaknesses of fossil fuel imports and keeps regions out of geopolitical upheavals and price fluctuations. Algae production can also be incorporated in other settings, including non-arable land, saline or wastewater, and industrial CO_2 emissions, which further increases the energy independence of the region, using the underutilised resources as well as minimising the need for freshwater [12], [13]. This type of localised production contributes to energy security as well as providing regional economic opportunities through sustainable biorefinery facilities and models of the circular economy [1]. A number of case studies are used to demonstrate the successful implementation and possible scalability of algal biodiesel in various geographic areas. Indicatively, areas with high solar energy availability, and access to seawaters or salty waters have shown high areal productivities, in some cases of up to 1925 liters of bio-diesel per square meter per year, thus supporting the feasibility of using algae as a source of biofuel in a localized area [14]. Moreover, pilot projects based on the use of wastewater as a source of algae cultivation have shown the two-fold advantages of sustainable energy generation and wastewater treatment, which is a synergistic strategy that helps to achieve the environmental goals and increase the production of biofuels [15]. Although the present world scale production is insignificant when compared to fossil fuel production, technology usage in growing systems, genetic strain selection, and downstream processing are gradually addressing the economic and scale challenges, and algal biodiesel is becoming a worthwhile addition to the national and regional energy mixes [9], [12]. To summarize: green algae's rapid rate of biomass production and ability to be locally cultivated makes it a strategic, renewable fuel source that can diversify energy supplies and decrease dependence on fossil fuel imports. Algal biodiesel can increase resilience to disruption of supply chains due to its incorporation into the regional energy infrastructure of many nations, as well as assist countries in their transition to sustainable energy use throughout the various climate zones of our world [1, 2, 13].

2.2. **Comparative Analysis :** The energy density of algal biodiesel is similar to that of traditional diesel fuel, due to the relatively high amount of lipids contained in algal biomass (up to 75%) and therefore making it an effective means of providing a liquid fuel for transporting vehicles compared to other renewables (e.g., solar and wind) which have significantly lower energy densities and thus depend on natural conditions that are not always available at certain times of year; also ethanol is a biofuel that has a lower energy density (about 24-26MJ/kg) than diesel or biodiesel [1], [2], [16]. Algal biodiesel has the potential to be highly scalable due to the high growth rates of algae, this capability to grow on unproductive land and wastewater, and the possibility to sequester CO_2. These properties minimize competition to food crops and arable land as is the case in first- and second-generation biofuels. Nevertheless, the commercial scalability is at this time hampered by low biomass concentration and high harvesting and processing expenses. Comparatively, solar and wind power have reached tremendous scalability at a falling cost, but are restricted in their location and intermittency. The availability of land and agricultural inputs limits traditional biofuels [3], [17], [18]. In contrast to solar and wind power, which are sensitive to the weather and daylight and therefore need some form of storage or grid management to maintain the supply of a constant flow, algal biodiesel provides a steady, predictable flow of liquid fuel that is independent of weather. This renders it especially useful as transport fuel, which needs to be available on demand. Other biofuels are also a continuous supply as long as there is biomass available, although they are frequently constrained by harvesting cycles [2], [19]. At present, algal biodiesel is characterized by high production costs in the form of costly cultivation mechanism, harvesting, extraction and drying. These costs are necessary to be reduced through technological advancements like advanced photobioreactors, genetic strain optimisation and integrated biorefineries. In comparison, solar and wind technologies have enjoyed the advantages of fast cost reductions and economies of scale resulting in competitive, levelised costs of electricity. The economics of other biofuels have a wide range; first and second generation biofuels are commonly dependent on subsidies and favorable policies but have difficulty with feedstock and land prices. Algal biodiesel infrastructure investments are dedicated bio-refineries and fuel distribution and engine technology adjustment, solar and wind energies need grid upgrades and other biofuels frequently utilise existing fuel infrastructure [1], [17], [20]. Life cycle analysis demonstrates the potential of algal bio diesel to achieve a reduction in greenhouse gas emission by up to 90 percent relative to fossil diesel, which is facilitated by CO_2 sequestration in the photosynthetic process of developing biomass and high lipid productivity. Wastewater streams can be used to moderate water consumption though the energy requirements of the processes are high. The solar and wind energy has minimal operational emissions but has had GHG emissions during the manufacturing and installation stages. The conventional biofuels may reduce GHG emissions and often require land-use change, high water and fertiliser requirements, which may have impact on biodiversity and ecosystem health [1], [17], [21]. Although algal biodiesel production has good qualities, there are major obstacles to its production in technological aspects such as optimisation of large scale cultivation, strain development, harvesting of biomass, extraction of lipids and upgrading of fuels. Economic barriers entail the presence of high capital and operation expenses that make the market competitiveness challenging and requires policy support, research investment and process integration strategies. Algal biodiesel has been tested in compatibility programs with engine oils and has been found to be comparatively the same as fossil diesel in compression ignition engines, but there are some increases in NOx emissions. Solar and wind technologies are relatively developed, but they need improvements in storage and grid integration systems. Other biofuels however are constrained by the feedstock sustainability and land competition [1], [2], [3]. A distinctive benefit of algal biodiesel is the fact that it can be produced based on decentralized production with a variety of resources, thereby improving the energy security of the region and reducing the level of fossil fuel reliance. As technologies advance further to address existing constraints of cost and scale, algal biodiesel may turn into an essential element of national policies that will seek to achieve energy independence and decarbonisation, especially in energy sectors that are difficult to electrify. Solar and wind energy would have greater contribution to electricity independence but cannot replace liquid fuels completely. The other biofuels aid in reduction of imports, but they are constrained by resource availability [1], [2], [3]. Summing up, algal biodiesel has high energy density and non-intermittency with high environmental virtues and potential to be produced in scale on non-arable land. Even though economic and technical issues have been causing its slow adoption in the recent past, it can still be a viable renewable biofuel that can help in diversifying energy portfolios and achieving national energy security goals among other renewable energy sources, which include solar, wind and conventional biofuels.

3. Regulatory Frameworks

3.1. **Existing Regulations:** The commercialisation and broad-scale introduction of algal biodiesel strongly depends on its adherence to the recognised standards of biodiesel quality, the regulations on applicable emissions, and the favourable policy incentives. Biodiesel quality criteria, e.g., the American Society of Testing and Materials (ASTM) D6751 and the European Norm (EN) 14214 give thorough specifications of oil characteristics, e.g. the viscosity, cetane number, the oxidative stability, cold filter plugging point, and the acid value. These standards guarantee that biodiesel fuels can work well in compression-ignition engines without any damage or loss of performance. The empirical research evaluating algae-derived biodiesel such as the ones derived in species like Chlamydomonas and Chlorella have shown that they always met the requirements or were very close to the requirements of ASTM D6751 and EN 14214 and assert that algal biodiesel is commercially viable, given the prevailing regulatory contexts. Indicatively, biodiesel of Spirogyra elongata and other algae growing in freshwaters showed the fatty acid methyl ester profiles and fuel parameters (viscosity, cetane number and iodine value) within a range acceptable to these standards. This standardization encourages the use of bio-diesel, in its neat form (B100) or as a blend of bio-diesel with petroleum diesel, as an alternative or as a supplement to petroleum diesel [22], [23]. Concerning the regulations of emissions, Reactivity Controlled Compression Ignition (RCCI) engines provide a viable platform to combine the renewable fuel, including algal bio-diesel, due to the ability to achieve a high level of control of the combustion reactivity, which results in significant increases in fuel efficiency and emissions profiles. Emission requirements applicable to RCCI engines, including Euro VI on heavy-duty engines and Stage V on waterways inland, place heavy restrictions on the quantity of nitrogen oxides (NOx), particulate matter (PM), and hydrocarbons emissions. It has been shown through experimental studies that algal biodiesel blends utilized in RCCI engines can achieve significant carbon monoxide (CO), hydrocarbons (HC), and particulate emissions and still experience no difference in engine performance, as compared to conventional diesel. There were also small rises in NOx emissions, which are controllable by using optimum ratios of fuel blending and more sophisticated combustion control measures which are inherent in RCCI technology. Besides, new fuel blends that include algal biodiesel and other renewable substances have been demonstrated to meet ultra-low emission standards, thereby meeting or even surpassing the existing policy (regulatory) standards [2], [24], [25], [26]. Policy wise, there are policy mandates and incentives related to renewable fuel, which has a strong impact on entry and growth of algae-based biodiesel. Regulatory tools, including blending quotas, tax credits, and biofuel certification systems encourage the use of biodiesel in the transportation fuel mix. Indicatively, the government regulations that demand minimum percentage of renewable component in diesel fuel generate a direct demand of biodiesel blends. Fiscal policies, such as subsidies on production and tax subsidies, can be used to offset the increased initial cost of production of algal biodiesel, which has been struggling economically despite its environmental advantages. Also, most of the national policies encourage research and development activities in order to ease the bottlenecks in production and increase its sustainability status. Nevertheless, the penetration of algal biodiesel is still at an infancy stage compared to other biofuels and this is attributed to the fact that technology and the scale-up barrier, hence, the requirement of combined policy frameworks that would improve supply side and demand-side support [1], [27], [28]. To conclude, algal biodiesel is in compliance with the specifications of ASTM and EN quality standards of biodiesel, and it portrays that it is compatible with regulatory fuel requirements. RCCI engines powered by blends of algal biodiesel tend to comply or even exceed with the requirements of the emission regulations, especially those of CO, HC and PM, and optimised combustion strategies address the issue of NOx. Incentives and renewable fuel requirements are very crucial in promoting the use of algal biodiesel but more policy support and technology improvement is needed to address the current economic and production barriers. This regulatory fit makes algal biodiesel a viable and viable alternative fuel in the existing and new energy and environmental models.

3.2. **Potential Regulatory Developments infrastructure requirements:**In recent years, there has been an increasing number of global policies supporting the use of low carbon fuels and advanced biofuels such as algae based biodiesel, which will be an important part of achieving the world's goal to reduce greenhouse gas emissions and transition to sustainable forms of energy. Policies created with renewable fuel standards, blending requirements, carbon intensity reductions and others have been put in place to take advantage of the environmental benefits associated with advanced biofuels that are produced from nonfood sources. The policies support innovation and investment into technologies that improve the lifecycle of emissions and resource efficiency while aligning the domestic policies with the international commitments made in the Paris Accord aimed at limiting global warming [29], [30]. Support from the government for research and development, subsidies for production and construction of infrastructure that help support the introduction of algal biodiesel is critical in facilitating the development of algal biodiesel by assisting with economic and technical barriers. Some examples of financial incentives include tax credit programs to provide sustainable biofuels, funding for algae cultivation methods and refiners, pilot or demonstration projects minimize potential commercial risks associated with algal commercial production. Investment in biorefinery infrastructure, distribution systems capable of transferring biodiesel blends, and other biorefinery infrastructure will help to overcome the problems of high costs and supply chain complexities that restrict algal biodiesel from being competitive [31], [32]. The international climate agreements, especially the Paris Agreement, have a significant influence on the national policies on biofuels since they incorporate binding obligations to cut down on greenhouse gases. As nations pursue the pathways to net-zero emissions, they are incorporating the advanced biofuel implementation into their renewable energy, sustainability requirements, and emission trading initiatives. In this international policy context, strict certification programs to certify carbon reduction and feedstock sustainability and to establish market incentives by carbon pricing and support of fuels with low-carbon emission profiles which have been proven are promoted. As a result, there is an advantage of algal bio-diesel development in the increased focus on renewable liquid fuels capable of decarbonising less electrifiable transport sectors [29], [33].Nonetheless, there are regulatory issues that come with the development of the algal biodiesel. Sustainability certification is a complicated procedure that involves strict scrutinies of greenhouse gas emission in lifecycle, land and water usage effects, and biodiversity results. The infancy of the algae feedstock manufacturing presents uncertainty in terms of setting up generally acceptable standards and traceability of the products. There is also the problem of cross-border trade due to the national differences in regulations, quality standards, and sustainability standards, which may divide markets and make supply chains difficult when it comes to the international biofuel trade. Further deterrence of private investment and long-term planning may be caused by regulatory uncertainty connected with changing policies and technological advances [15], [29].

Overall, the current regulatory environment of algal biodiesel is increasingly influenced by the policy of advanced low-carbon biofuels, which is backed by the government subsidies and global climate regulations. The success of the algal biodiesel in relation to sustainable energy and climate policies will depend on overcoming the challenges in certification, feedstock sustainability assessment, and harmonisation of trade regulation, which will unlock the full potential of algal biodiesel.

4. Public Perception and Acceptance

4.1. **Societal Awareness:** As such, the overall public knowledge of the economic, environmental and social impacts of biofuels is mixed (only partially known) with respect to public interest in these fuels and is very much related to how well the public understands these fuels and other associated aspects; and there appears to be a significant correlation between public understanding and public acceptance. While recent research conducted by Centers for Sustainable Energy in four states (North Carolina and Tennessee) indicates good levels of support for biofuels, support for biofuels is dependent on a variety of other factors such as cost-competitiveness, vehicle compatibility, and concerns over the potential impact of biofuels on food prices and environmental quality, to name just a few. These findings indicate that there is a strong correlation between public perceptions of biofuels, perceived advantages of biofuels, and perceived disadvantages of biofuels, as well as there being a critical need for transparent communications regarding biofuels to address these perceptions [34].

Educational Campaigns through media outreach and promotional events have been extremely effective in changing the public perception of biofuels. Today, social media has emerged as a critical source for spreading information to the general public. Those campaigns utilizing attractive visual content, as well as engaging the community, will be the most effective at creating awareness and positive attitudes toward renewable fuels. Additionally, Public Service Media play an important part by providing high-quality reporting, combating misinformation and increasing media literacy, thus enabling individuals to evaluate critically information about biofuels. Developing individualized communication strategies through trustworthy communication methods that do not expose individuals to excessive advantage or risk, can help to generate an informed opinion about biofuels, and facilitate greater acceptance and support for all forms of biofuels, including algal biodiesel [35-66].Misinformation and lack of information are major barriers to the acceptance and use of these technologies by the public. Social media is often used to spread false or incorrect information about biofuels very quickly, aided by platform algorithms and echo chambers created by users. These false or misleading messages can create doubt or fear, usually exaggerating the negatives related to the economy or harm to the environment, so that sustainable solutions for bioenergy cannot be realised in the area being discussed. Research has shown that filter bubbles and personalised content add to a person's already established bias, making it difficult for critical thinking to dominate. To combat these problems, digital literacy programs will need to be established; use of technological tools to identify false information will need to be employed; and authoritative information will be needed to counteract falsehoods and correct any informational voids [37], [38], [39].All in all, the biofuels and the algal biodiesel awareness in society is subject to change, though it is susceptible to all the effects of media framing and misinformation. Educational campaigns that are well planned and use digital media effectively with clear and credible sources of information are necessary in enhancing the awareness and approval of the people. It is essential to overcome misinformation to promote informed opinion of the population and long-term social support of renewable biofuel policies and implementation.

4.2. **Barriers to Adoption:** Implementation of algal biodiesel as a green source of energy has various obstacles, which are largely cultural, economical, infrastructural, and perception related. These issues will be critical in the development of effective strategies to address resistance and enable the integration into the market. People prefers conventional fossil fuels through their deep-rooted traditions show skepticism toward algae biofuels. The public and business leaders must learn about algal biodiesel before they will accept it because they currently lack understanding of its advantages and operational capabilities. The existing cultural obstacles to adopting new technologies become harder to overcome because people want to know how algae production and processing will affect the environment and whether the fuel will work with current engines and be safe to use. The established fossil fuel system proves difficult to change through algae biofuel implementation because historical proof shows petroleum products have always been the main energy source in areas where this phenomenon exists[1], [2].

The expensive nature of production for algal bio-diesel is a significant economic barrier to widespread adoption of algal biodiesel. The algal bio-diesel production process requires a great deal of energy and involves costly processes related to farming, harvesting and extraction of lipids. This increased production cost ultimately leads to a higher final cost for the resulting fuel and therefore makes it less competitive with current fossil fuels.Because of relatively low amounts produced thus far, it has also not been possible to achieve economies of scale that would produce lower long-term costs. Partnering with biorefineries producing co-products of value has been identified as an important method to enhance the economic feasibility of algal biodiesel, however, this increases the complexity of the operational and financial structure, making them less attractive [1], [9], [40].Algal biodiesel cannot compete for the price necessary for algal bio-diesel to achieve the degree of global adoption necessary for wide-scale industry and consumer use without significant policy intervention, e.g. tax incentives and blending mandates [41].

Another challenge to consumers is the low level of development of infrastructure to distribute and refuell algal biodiesel. Current fuel supply chains and storage systems are pre-dominantly prepared to handle petroleum based fuels and will need modification and capital to suit biofuels including algal biodiesel. The absence of standardised fuel formulations and low supply in the points of sale creates some concerns on how convenient it is to operate, compatibility with different engines, and maintenance. The above aspects bring about the perceived inconveniences that compromise the consumer confidence and the industry readiness to use algal biodiesel on a large scale [1], [2], [41].

The combination of stakeholder involvement and open communication with good examples and effective policies will succeed in overcoming these barriers. The process of participatory decision-making together with extended supplier interactions and educational programs for fleet operators and policymakers will build trust while decreasing resistance which stems from cultural beliefs. The scientific communication about algal biodiesel advantages needs to use accurate information that demonstrates environmental advantages and engine performance to correct public misunderstanding about its applications. The demonstration and pilot projects of algal biodiesel serve as essential evidence-based initiatives which validate this technology while creating market recognition. The algal biofuel market requires policymakers to provide incentives through subsidies and tax credits and blending mandates and regulations which will drive consumer demand while creating essential market infrastructure. The public acceptance of algae biofuel production will increase through the implementation of wastewater treatment processes and circular economy practices. The ongoing research and technological development efforts which aim to decrease algal fuel production costs and enhance cultivation and processing techniques and fuel properties need to succeed because they address both economic and technical obstacles[1], [2], [41], [42].

The implementation of algal biodiesel faces three main challenges which include cultural biases together with financial constraints and inadequate infrastructure. The solution to these challenges requires educational programs together with policy enforcement and technological progress and effective leadership to establish trust and economic viability and accessibility which will enable algal biodiesel to become a major component in energy transition.

5. Conclusion

Algal biodiesel is a very promising renewable energy source that goes a long way in ensuring energy security and environmental sustainability. Its properties make it a great source of fuel because of its high lipid productivity, fast biomass growth, and capacity to remove carbon dioxide, thus, it can generate large amounts of fuel without any arable land or food resources. The production efficiency and the quality of fuel has continued to rise due to the technological improvements, such as genetic engineering, better cultivation, and better extraction of lipids. These enhancements allow the compatibility of algal biodiesel with compression ignition engines, including Reactivity Controlled Compression Ignition (RCCI) engines where algal bio-diesel has shown good combustion properties and significant changes in the harmful emissions which include carbon monoxide, hydrocarbons and particulate matter though there are slight increases in NOx emissions which need additional management.The effective introduction of algal biodiesel in energy market is highly associated with the changing regulatory frameworks and policies. The set of fuel quality standards, emissions, and renewable fuel requirements offer a basis to its use, and new low-carbon fuel policies, subsidies, and global climate treaties, including the Paris Agreement, help in enabling favourable conditions to increase the algal biodiesel production. Nevertheless, there are still regulatory issues, such as certification procedures, feedstock sustainability standards, and harmonisation of cross-border trade, which have to be managed so that the growth of these fuels can be sustainable, and they may be accepted by the market.The second vital component which determines whether algal biodiesel can succeed depends on how society views this biofuel. The existing knowledge among people is not adequate and is usually based on false information or lack of information which predetermines cultural inclination to use traditional fuels and distrust to new technology. The barriers which exist in the situation can be eliminated when educational activities and open dialogue and particular communication methods through media and demonstration projects are implemented. Economic issues of production expenses and infrastructure preparedness also play a role in the reluctance of the situation, and such integrated approaches are required that will combine innovations in the engineering field, encouragement of policies, and engagement of the stakeholders. Simply put, the achievement of the maximum potential of algal biodiesel will necessitate a multi-dimensional solution whereby the technological innovation, solid regulatory backing, and proactive involvement of the population will intersect. By combining these dimensions, the conversion of algal biodiesel to a niche to a substantive part of the national and global energy security and reduction of environmental impacts can be achieved, which will lead to a sustainable and resilient energy future.

Declaration of competing interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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