UMT PRESS

Journal of Sustainability Science and Management
Journal Homepage: https://jssm.umt.edu.my
eISSN: 2672-7226
DOI: http://doi.org/10.46754/jssm.2026.03.011

STIMULATING LEARNING FOR SUSTAINABLE BIOFUEL DEVELOPMENT AND SOCIOECONOMIC ADVANCEMENT

MOHAMMAD ALIFF SHAKIR[1], MARDIANA IDAYU AHMAD[1]*, FOZY BINHWEEL[1], FATIN ZAFIRAH MANSUR[2], PAVAN JUTUR[3], VITTORIO VENTURI[4], NOR HAWANI SALIKIN[1] AND ABDUL KHALIL H.P.S.[5]

[1]School of Industrial Technology, Universiti Sains Malaysia, 11800 Gelugor, Penang, Malaysia. [2]Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26300 Kuantan, Pahang, Malaysia. [3]International Centre for Genetic Engineering and Biotechnology, ICGEB Campus, Aruna Asaf Ali Marg, 110 067 New Delhi, India. [4]International Centre for Genetic Engineering and Biotechnology, Padriciano 99, 34149 Trieste, Italy. [5]Faculty of Business, Hospitality and Technology, Universiti Islam Melaka, Batu 28, Kuala Sungai Baru, 78200, Melaka, Malaysia.

**Corresponding author: mardianaidayu@usm.my*

ARTICLE INFO

Article History:
Received: 14 May 2024
Revised: 2 October2024
Accepted: 21 October 2024
Published: 15 April 2025

Keywords:
Stimulating learning, biofuel, sustainability.

ABSTRACT

The use of biofuels as a sustainable and eco-friendly alternative to conventional fuels is getting more widespread globally. The development of sustainable biofuel production is crucial not only for environmental reasons but also for socioeconomic growth. However, to fully realise the potential of biofuels, it is essential to understand the sustainability and socioeconomic aspects of the sector. This review examines recent advancements in sustainable biofuel production and commercialisation, with an emphasis on second- and third-generation biofuels known for their advanced and sustainable characteristics. The study explores how stimulating learning about the sector can drive the development and adoption of biofuels, contributing to sustainability goals and socioeconomic benefits. It analyses the current status of biofuel production, consumption and available production facilities, considering the socioeconomic factors such as energy exports, imports, and trades. The study concludes that stimulating learning about biofuels can play a vital role in their adoption, leading to sustainable development and significant socioeconomic advantages.

Introduction

Biofuels are a form of energy extracted from organic materials produced by plants and other living organisms, collectively referred to as biomass. Biofuels are predominantly obtained from renewable sources such as agricultural outputs, crucial harvesting processes, forests, and waste streams as shown in Figure 1. The renewable nature of biofuels makes them attractive alternatives to depleting fossil fuel sources. This renewability makes them significant in providing sustainable energy solutions (Malode *et al.*, 2021; Shakir *et al.*, 2023). The adoption of biofuels could decrease reliance on fossil fuels and address the growing issues related to climate change and greenhouse gases emissions (Estevez *et al.*, 2022).

Nevertheless, the environmental sustainability of biofuels involves complex considerations such as the type of biomass used, the methodologies involved in their production, and the entire lifecycle of the fuel. The production of first-generation biofuels from food crops like corn and sugarcane has ignited discussions about food security and the effects on land usage (Deora *et al.*, 2022). These issues have redirected attention to second and third-generation biofuels, sourced from non-food biomass such as waste materials, algae,

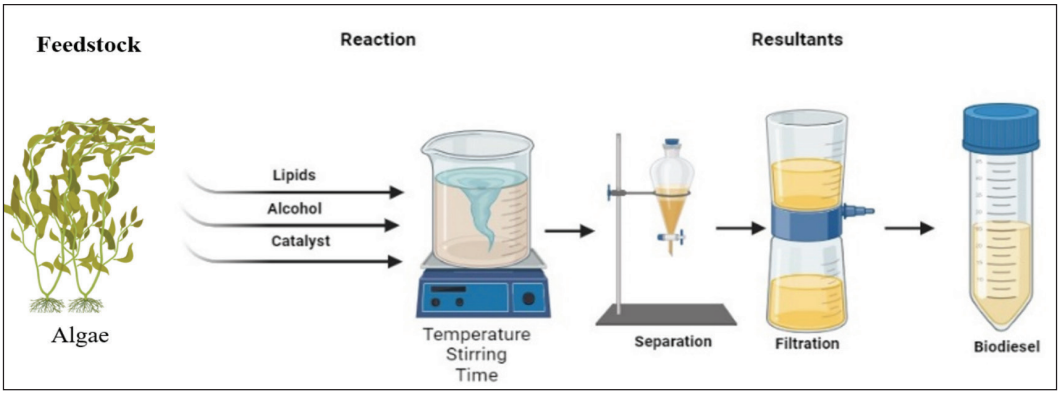

Figure 1: Example of production process of biofuel using algae as feedstock

and perennial grasses (Mat *et al.*, 2020). While much research has been done on the technical advancements in second- and third-generation biofuels, this review fills a crucial gap by examining the role of stimulating learning about advances in biofuel technology.

These advanced forms of biofuels offer enhanced sustainability advantages such as significantly lower greenhouse gas emissions and minimised competition with food production, positioning them as more environmentally responsible and sustainable energy solutions (Neupane, 2023; Shakir *et al.*, 2023a). Furthermore, the cultivation of feedstock for biofuels could increase rural development and job creation, thereby improving the socioeconomic environment. Compared with previous studies that focus on the environmental benefits of biofuels, this review emphasises the socioeconomic impacts biofuel production can have on rural development and job creation (Patwardhan *et al.*, 2022). However, it is imperative to weigh these advantages against possible environmental consequences such as biodiversity loss and the strain on water resources. Hence, the true sustainability of biofuels depends on a comprehensive approach that takes into account ecological, economic, and social factors to ensure a balanced and responsible utilisation of these energy sources (Tudge *et al.*, 2021). This all-encompassing viewpoint emphasises the critical role of strategic planning and astute policymaking in leveraging the capabilities of biofuels for a sustainable future. Biofuels offer a promising renewable energy option, but they need careful evaluation and management to ensure they support environmental sustainability and protection.

The progression of biofuels as a viable energy solution encompasses more than just technological and economic aspects, it is deeply rooted in education and learning. This review aims to fill the gap by focusing on how education from elementary schools to higher education plays a pivotal role in stimulating innovation and driving the adoption of biofuels. Central to the advancement of biofuels is the need to comprehend intricate biological processes, technological developments, and ecological repercussions (Anto *et al.*, 2020). This broad spectrum of knowledge is essential for both innovators in biofuel technology and end-users adopting these sustainable methods. Educational efforts in this area must address different levels, from raising basic awareness about the advantages and limitations of biofuels to offering in-depth training in biofuel production and technological applications (Levine *et al.*, 2021). Elementary education has a crucial role in establishing a fundamental understanding of sustainable energy. By including biofuel-related topics into school curricula, students are exposed to the core concepts of renewable energy from a young age (Rosales *et al.*, 2023). This early exposure is crucial for developing not

only academic knowledge but also a practical understanding of how sustainable energy sources can address global environmental challenges. Through hands-on activities, projects, and interactive lessons, students can be introduced to concepts such as biomass, energy conversion, and the environmental benefits of biofuels. This approach to stimulating learning helps foster curiosity and critical thinking skills, encouraging students to explore the science behind renewable energy solutions.

This review also addresses the gap in connecting educational efforts with long-term impacts, showing how stimulating learning in early education can shape the future workforce in biofuel technology. By nurturing interest and awareness at an early stage, elementary education serves as the first step in cultivating the next generation of scientists, engineers, and advocates who will drive future innovation in biofuel technology. Early educational engagement also contributes to building a society that appreciates and actively seeks to implement renewable energy sources. Moreover, this foundational education plays a critical role in shaping the attitudes of students towards sustainability, ensuring they develop a mind-set that values long-term environmental stewardship.

Higher education and vocational training are equally critical in developing the specialised skills needed for biofuel production and innovation (Leibensperger *et al.*, 2021). Universities and technical institutes play a crucial role in advancing research and providing educational courses focused on biofuel technology, sustainable methods for biomass production, and environmental impact analysis. This specialised training is fundamental in cultivating a workforce skilled in the development and effective application of biofuel technologies (Saratale *et al.*, 2022). In addition, ongoing professional development and learning are crucial for keeping abreast with the rapidly advancing biofuel industry. Workshops, seminars, and online courses are vital platforms for continuous learning for professionals in the biofuel sector. These educational avenues not only contribute to the enhancement of their expertise but also facilitate the rapid dissemination and application of the most recent technological and scientific developments in the field (Bhatia *et al.*, 2022).

This review also addresses the gap in public engagement by looking at the importance of stimulating learning among citizens and stakeholders in biofuel technologies, an often overlooked aspect in biofuel research. Public education campaigns and community outreach initiatives play a crucial role in elevating the understanding and acceptance of biofuels among the populace. Educating citizens about the benefits and practical aspects of biofuels can catalyse a more substantial shift in society towards embracing sustainable energy practices (Saini *et al.*, 2021). Stimulating learning is fundamental to both the development and effective deployment of biofuel technologies. Cultivating a population that is knowledgeable and skilled at all levels, from grassroots advocates to industry experts is essential to unlocking the full potential of biofuels as a viable and sustainable energy resource.

This review explores the connection between stimulating learning, education, and biofuel development. It highlights the crucial role that educational strategies play in promoting sustainable biofuel development and understanding its socioeconomic impact, and offers a detailed understanding of the latest advancements in biofuel technologies. This review also addresses the gap in how educational initiatives can support not only technological advancements but also the broader socioeconomic impacts, contributing to a more comprehensive understanding of biofuel innovation. By doing so, it is hoped that policymakers, educators, industry leaders, and the general public will be informed about the importance of educational initiatives in sustainable energy.

Biofuels: An Overview

Biofuels are an essential element in the quest for sustainable and renewable alternatives to conventional fossil fuels. They are produced from renewable biomass, a key factor in their potential as a sustainable energy source. This attribute plays a vital role in lessening reliance on finite fossil fuel reserves and addressing environmental challenges such as climate change and greenhouse gas emissions, thus contributing directly to the aims of SDG 13 (Climate Action). Biofuels are instrumental in advancing SDG 7 (Affordable and Clean Energy) by offering cleaner energy options and facilitating the shift to more sustainable and renewable energy sources (Amerit *et al.*, 2023). The categorisation of biofuels is determined by the biomass source and the production technology, reflecting the progression of this sector towards more effective and eco-friendly options. The expansion of the biofuel industry, as shown in Figure 2, not only aids in mitigating the environmental impact of energy consumption but also opens avenues for economic growth and job creation. This expansion is in line with SDG 8 (Decent Work and Economic Growth), underscoring the capacity of biofuels to stimulate economic development while generating sustainable and valuable employment opportunities (Ambaye *et al.*, 2021). Adopting biofuels means committing to a more sustainable energy future. It also supports global efforts to achieve key goals in economic progress, social advancement, and environmental protection, as outlined in the SDGs.

Types of Feedstock for Biofuels

Public discourse on biofuels often revolves around their renewability as a result of their regenerative sources. This is contrasted with fossil fuels, which are finite and come from old biological materials. Biofuels emerge as an ecologically responsible alternative to conventional fossil fuels, possessing significant potential to markedly reduce greenhouse gas emissions and curtail dependence on the dwindling fossil fuel reserves. A comprehensive and academic exploration of biofuels begins with an examination of the first-generation biofuels, which are extracted from food crops like corn, sugarcane, and soybean oil (Esmaeili *et al.*, 2020). However, this first generation of biofuels sparked concerns regarding food security and land utilisation, leading to the exploration and development of more sustainable and less contentious alternatives.

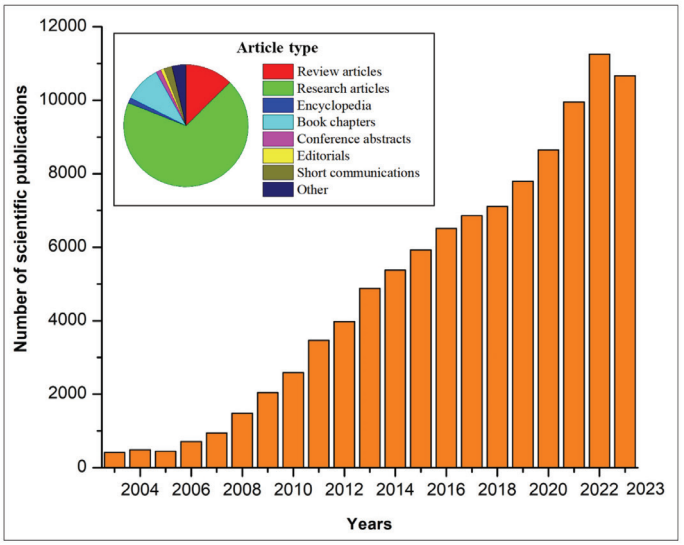

Figure 2: Accelerated number of publications about development biofuel in the past two decades

Second-generation biofuels represent a significant advancement, as they are derived from non-food biomass. This category encompasses a wide array of agricultural residues and forest by-products such as wood chips, various grasses, and non-edible plant parts (Pabbathi *et al.*, 2021; Shakir *et al.*, 2023b). These biofuels address the critical issue of food versus fuel competition inherent in first-generation biofuels by utilising waste or specifically cultivated energy crops, thus not encroaching on food supplies. A good example of second-generation biofuel is cellulosic ethanol, derived from lignocellulose biomass (Patel & Shah, 2021). Engaging academically in this area necessitates an in-depth exploration of the complex biochemical pathways and cutting-edge technological processes required to efficiently convert such biomass into functional fuels.

The evolution continues with the advent of third-generation biofuels, where algae emerges as a key resource (Sadatshojaei *et al.*, 2020). Algae can produce biofuels like biodiesel and bioethanol more efficiently than conventional crops, and their ability to grow in different environments without using farmland is a major advancement in biofuel development, as shown in Figure 3 (Wong *et al.*, 2022). The academic inquiry in this realm extends to the investigation of advanced biotechnological approaches, algae cultivation methodologies, and the extraction of oils and other valuable compounds from algae. A significant gap addressed by this review is the lack of focus on how education can keep pace with the rapidly evolving nature of third-generation biofuels, particularly algae-based fuels. The importance of stimulating learning in these areas cannot be overstated. The field of algae biofuels requires specialised knowledge in algae cultivation, biotechnological processes, and environmental sustainability.

This study adds value by advocating for interdisciplinary educational frameworks that integrate biological sciences, biotechnology, and environmental engineering, equipping students and professionals with the skills to innovate in this complex field. By fostering an environment of continuous learning, both in academic institutions and through professional training programmes, future biofuel researchers and engineers can be better prepared to tackle the unique challenges of algae-based biofuel production. This includes mastering the intricate processes of algae cultivation, optimising biotechnological extraction methods, and ensuring that these advancements align with broader sustainability goals. By stimulating learning, educational efforts can drive innovation, ensuring that the next generation of biofuel experts is ready to contribute to the sustainable and efficient production of algae-based biofuels.

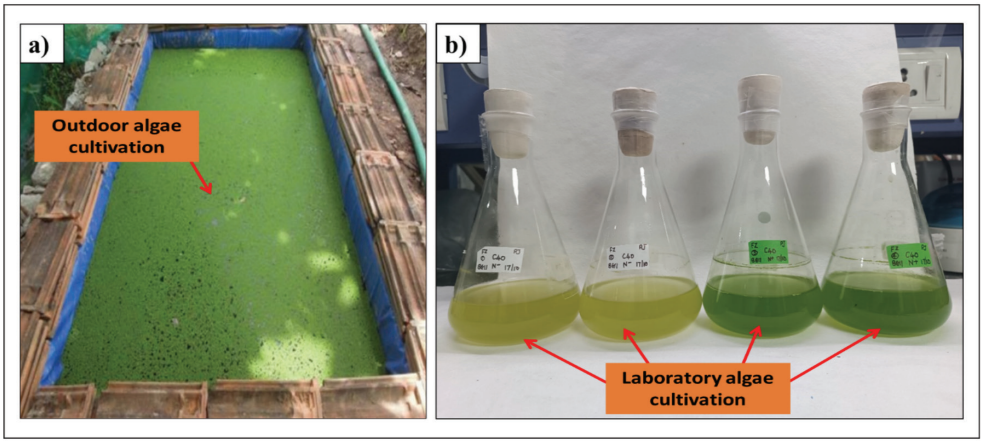

Figure 3: An example of (a) algae cultivation in a controlled outdoor pond and (b) the process of algae culture in a laboratory at different conditions for biofuel extraction

Educational Framework for Biofuel Development

The successful development and widespread adoption of biofuels require a robust educational framework that fosters learning across multiple levels. Education plays a crucial role in equipping individuals with the knowledge and skills needed to drive innovation in biofuel technologies. This framework seeks to address the gaps in current biofuel education by focusing on three core elements: Raising basic awareness, providing professional training, and encouraging public engagement. First, at the foundational level, it is essential to raise awareness about the benefits, challenges, and potential of biofuels. Stimulating learning at this early stage involves incorporating biofuel education into primary and secondary curricula to create an understanding of renewable energy sources and their environmental significance (Dishadewi *et al*., 2020). By educating students at a young age, we can lay the groundwork for future generations to contribute meaningfully to the biofuel sector.

Second, professional training programmes must be developed to address the rapidly evolving technical and scientific demands of biofuel production. These programmes, aimed at students, researchers, and professionals, should integrate interdisciplinary learning, combining knowledge from relevant scientific and engineering fields (Alizadeh *et al*., 2020). This stimulating learning approach ensures that professionals are equipped to tackle the complex challenges in biofuel development such as the efficient conversion of biomass, scaling production processes, and ensuring the economic viability of biofuel technologies. Lastly, public engagement plays a vital role in fostering societal acceptance and support for biofuels. Stimulating learning through public education initiatives, community outreach programmes, and informational campaigns is key to increasing awareness of the environmental and socioeconomic benefits of biofuels (Armstrong, 2021). An informed public is more likely to support policies and practices that favour the transition to renewable energy, which drives demand for biofuels and encourages investment in this growing sector. These three elements such as basic awareness, professional training, and public engagement, create a comprehensive educational framework to stimulate learning and innovation in biofuel development. Addressing these needs supports the long-term success and sustainability of biofuel technologies, contributing to a cleaner energy future.

Model Description and Key Assumptions

The model presented in this review emphasises the integration of interdisciplinary learning, continuous professional development, and public engagement to stimulate learning in the context of biofuel development (Blanchard *et al*., 2021). At the core of the model is the assumption that an interdisciplinary approach is crucial for fostering a comprehensive understanding of biofuel technologies. By integrating knowledge from fields such as environmental science, chemical engineering, and biotechnology, the framework encourages collaboration across disciplines. This interdisciplinary knowledge is essential for equipping learners and professionals with the skills needed to address challenges in biofuel production, including sustainability, efficiency, and scalability.

The model also assumes that continuous professional development is critical, given the rapid pace of advancements in biofuel technologies. Ongoing education through workshops, seminars, and online courses can stimulate learning and ensure that professionals in the biofuel sector remain proficient in the latest technological innovations (Kotsis, 2024). This approach helps to maintain a workforce capable of effectively applying new technologies and methods in the biofuel industry. Another key assumption is the importance of public engagement in driving societal acceptance and support for biofuels. Public education campaigns and community outreach initiatives are designed to stimulate learning by increasing awareness of the benefits of biofuels (Leibensperger *et*

al., 2021). The model rests on the idea that an informed public can foster greater demand for renewable energy, which in turn supports the growth of the biofuel sector.

In addition, the model assumes that educational efforts will have a significant socioeconomic impact. By stimulating learning at various educational and professional levels, the development of biofuels is expected to lead to job creation, rural development, and a reduction in reliance on fossil fuels (Hanna *et al*., 2024). Furthermore, it is assumed that these educational initiatives will support policymakers by equipping them with the knowledge needed to design and implement supportive biofuel policies. Lastly, the model also assumes that educational initiatives will align with sustainability goals, particularly in terms of reducing greenhouse gas emissions and promoting renewable energy (Ebadian *et al*., 2020). By embedding sustainability concepts into biofuel education, the model envisions a new generation of professionals and scientists who are committed to developing environmentally responsible energy solutions. This focus on stimulating learning supports both national and global efforts to mitigate climate change and foster sustainable energy systems.

Current State and Challenges in Biofuel Development

The landscape of biofuel innovation is marked by significant strides, yet it faces a series of hurdles that require not only technological advancements but also a strong focus on stimulating learning to equip individuals with the knowledge and skills needed to tackle these challenges. The progress in biofuel technology has been substantial, with the emergence of second and third-generation biofuels garnering attention for their eco-friendliness and minimal impact on food resources (Ganguly *et al.*, 2021; Müller *et al.*, 2023). Despite these advancements, scaling up these technologies for broader application presents distinct challenges that can be addressed only by fostering a culture of continuous education and innovation.

Technological Challenges

Converting lignocellulose biomass into fuel is a crucial part of second-generation biofuels, as it uses non-food sources such as agricultural residues, wood chips, and grasses. However, the complex biochemical processes required to break down lignocellulose into fermentable sugars, followed by the conversion into biofuels, involve multiple steps such as pre-treatment, enzymatic hydrolysis, fermentation, and purification. Each of these steps presents significant technical challenges and adds to the overall cost of production. The need for specialised enzymes, expensive catalysts, and advanced infrastructure has delayed the large-scale commercialisation of these fuels, despite their potential to significantly reduce greenhouse gas emissions (Lin & Lu, 2021). Moreover, the energy intensity of the process further complicates efforts to produce these fuels at a competitive price compared with conventional fossil fuels.

Third-generation biofuels, particularly those derived from algae are promising due to their higher productivity rates and reduced competition with arable land. Algae can be cultivated in diverse environments, including wastewater and saline ponds, offering greater flexibility in terms of land use. However, they face technological hurdles such as optimising algal growth conditions, improving the efficiency of nutrient uptake and minimising contamination during cultivation. The harvesting and extraction of oils from algae are also energy-intensive processes that require innovative solutions to make them cost-effective. Algal biofuels show great promise, but the high costs associated with these stages of production, coupled with the challenges of scaling up the technology for mass use have slowed their commercial viability (Bharathiraja *et al.*, 2022).

Stimulating learning plays a pivotal role in overcoming these technological challenges. By continuously educating professionals and researchers through interdisciplinary programmes, the biofuel sector can foster the innovation necessary to address the technical

complexities of second- and third-generation biofuels. Learning initiatives focused on advanced enzymatic processes, cost-effective scaling strategies, and improved cultivation techniques ensure that biofuel experts remain at the cutting edge of technology. This commitment to stimulating learning empowers the biofuel industry to overcome technical barriers, reduce production costs, and enhance the scalability and viability of biofuels as a sustainable energy source.

Environmental Considerations and Economic Barriers

Environmental considerations are paramount in the progression of biofuels. Although biofuels are celebrated for their potential to lessen greenhouse gas emissions, their ecological impact hinges on various factors, including land use changes, water usage, and the energy efficiency of their production process (Carrino *et al.*, 2020). The cultivation of crops for biofuels could lead to deforestation and biodiversity loss if not conducted responsibly (Yusoff *et al.*, 2021). Furthermore, the energy required to produce biofuels, from cultivation to processing, must be judiciously managed to achieve a beneficial energy output and true sustainability (Beig *et al.*, 2021). Integrating biofuels into existing energy frameworks and markets presents additional challenges such as developing suitable infrastructure for their distribution and modifying engines and vehicles for efficient biofuel utilisation (Alagumalai *et al.*, 2020).

Concurrently, policy and regulatory measures need to evolve alongside these technological advancements to bolster the biofuel sector, which includes providing incentives for research and development, and establishing guidelines for eco-friendly production methods (Ebadian *et al*., 2020). While biofuels have witnessed considerable development, they encounter a spectrum of technical, environmental, and economic hurdles. Addressing these challenges requires a comprehensive strategy that includes continuous technological innovation, effective environmental management, and supportive policy-making. Crucially, there must also be a strong focus on stimulating learning to drive the industry towards sustainable growth. Stimulating learning is essential in developing the expertise required to manage biofuel production responsibly. This ensures that land and water use are optimised, energy consumption is minimised, and environmental impacts are mitigated. Furthermore, stimulating learning is key to empowering professionals with the skills necessary to navigate the economic barriers of biofuel adoption, from improving production efficiencies to integrating biofuels into existing energy infrastructures. By promoting ongoing education, research, and public awareness, stimulating learning fosters innovation, responsible management, and economic viability within the biofuel sector.

The Imperative of Stimulating Learning

The rapidly evolving nature of biofuel technologies demands an equally dynamic educational response. As these technologies advance, they intersect with various disciplines, including environmental science, engineering, and economics, creating a multidisciplinary field that requires a broad and deep understanding. The imperative of stimulating learning lies in bridging the knowledge gap between current educational offerings and the evolving needs of industry (Voca & Ribic, 2020; Pascoli *et al*., 2022). This stimulating learning goes beyond traditional academic settings, extending to professional training, public awareness, and policy education. The goal is to create a well-informed community ranging from researchers and practitioners to policymakers and consumers, who are all pivotal in the widespread adoption and successful implementation of sustainable biofuel technologies.

Understanding the Educational Gap in Biofuel Technologies

The educational gap in biofuel technologies is noticeable across various levels and addressing it necessitates stimulating learning approaches. Academically, there is a pressing need for updated, interdisciplinary curricula that are in sync with the latest advancements in biofuel research and innovation (Narwane *et al.*, 2021). Many educational institutions have yet to fully embrace dedicated courses focusing on advanced biofuel technologies such as those related to algal biofuels or innovative methods for processing lignocellulose biomass (Sharmila *et al.*, 2022). This educational gap impedes the nurturing of specialised knowledge vital for ground-breaking research and effective production in the biofuel industry. Stimulating learning in these academic settings is key to closing this gap. In the professional sphere, stimulating learning can help existing professionals in the energy sector to stay abreast of the latest developments. The rapidly changing nature of biofuel technologies means that ongoing education is crucial for those currently working in the field (Alam & Tanveer, 2020). Moreover, the general understanding of biofuels in public and their benefits is often limited, impacting consumer acceptance, and market growth. Public education initiatives that stimulate learning are needed to uncover biofuels, addressing misconceptions, and highlighting their role in a sustainable future.

Furthermore, a significant gap exists in the realm of policy education. Policymakers, who are instrumental in moulding the biofuel industry through regulatory frameworks and incentives, need a comprehensive understanding of biofuel technologies and their potential impacts (Morone *et al.*, 2023). In the absence of this knowledge, policies might fall short in effectively fostering the development and wider adoption of these sustainable energy sources. To bridge these educational gaps, a unified effort is required from academic institutions, industry players, and governmental entities. This entails the revision and augmentation of academic curricula, provision of professional development programmes, execution of public outreach initiatives, and delivery of specialised education for policymakers. Therefore, stimulating learning across these areas is imperative for advancing the biofuel sector and solidifying its role in a sustainable energy future.

The Relationship between Education, Innovation, and Biofuel Development

The relationship between education, innovation, and biofuel development is symbiotic and foundational with stimulating learning to advance the field of sustainable energy. Education underpins this advancement, providing a comprehensive knowledge base and skill set that equips researchers, engineers, and entrepreneurial thinkers. This stimulated learning environment is essential for catalysing novel developments in biofuel technology (Postal *et al.*, 2020). This connection is crucial in the fast-changing biofuel industry, where new technologies and methods continuously reshape the scope and potential of the sector. By fostering interdisciplinary learning, education allows for the integration of diverse scientific and technical approaches. This integration enables breakthroughs that address both the technical and environmental challenges of biofuel production. Moreover, education promotes collaboration between academia, industry, and policy makers, ensuring that innovations are effectively translated into practical applications.

Higher Education as a Catalyst for Biofuel Innovation

Higher education institutions, including universities and specialised research centres, stand at the forefront of this evolution. These entities transcend the traditional role of academic instruction, emerging as pivotal centres of innovation and research in biofuels (Perea *et al.*, 2020). They provide a platform where theory meets practice, creating an environment ready for scientific discovery and technological innovation. Seminal advancements in biofuel

technology often originate within scholarly environments that are driven by stimulated learning approaches. These advancements span the spectrum from the development of groundbreaking biofuel production processes and efficiency optimisation, to the exploration of new sustainable biofuel sources (Zilberman *et al.*, 2022). These academic breakthroughs are key to advancing the biofuel sector.

Developing an interdisciplinary curriculum that integrates elements from environmental science, chemical engineering, and sustainability helps build a workforce skilled in handling the complex challenges of biofuel production (Afeyan & Cooney, 2020). It is crucial that these educational offerings remain flexible, integrating the latest scientific discoveries and industry developments to maintain their relevance and effectiveness. The innovation process in biofuel development also demands a comprehensive understanding that extends beyond scientific and technical facets. It involves a thorough grasp of the environmental, economic, and societal impacts associated with the production and utilisation of biofuels (Vickram *et al.*, 2023). This multidimensional nature of biofuel development is illustrated in Figure 4.

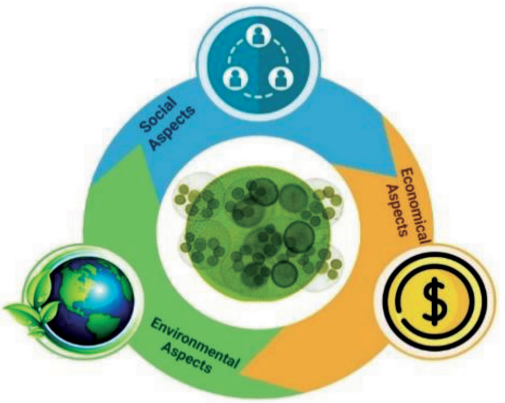

Figure 4: Illustration of the multifaceted impact of biofuel development towards encompassing environmental, social, and economic aspects

Consequently, education in areas like policy strategy, economic analysis, and environmental impact assessment becomes indispensable. Such a well-rounded educational approach is key to fostering a holistic perspective in biofuel innovation. This ensures that advancements in the field are not only technically sound but also environmentally sustainable and economically feasible, thereby contributing to the broader objectives of sustainable energy development.

Continuous Learning and Professional Development

The imperative of continuous education and professional advancement in the biofuel domain cannot be overstated. As the biofuel industry undergoes rapid evolution, the provision of ongoing educational opportunities for professionals is crucial. Educational initiatives such as workshops, seminars, and online training modules play a pivotal role in disseminating cutting-edge knowledge and technological advancements, nurturing a culture of relentless innovation and adaptability within the sector (Guddaraddi *et al.*, 2023). In summary, the relationship between education, innovation, and biofuel development is integral to the forward momentum of the biofuel industry. A strong educational infrastructure not only drives innovation. It also ensures that advancements in biofuel technologies align with sustainability, economic viability, and social responsibility. Addressing the educational requisites within this field is therefore a fundamental step in realising the comprehensive potential of biofuels as a vital component of a sustainable energy future. This academic focus is essential in steering the biofuel sector towards a trajectory that harmonises technological advancement with environmental sustainability and economic sensibility.

Educational Strategies for Biofuel Technology

The advancement of biofuel technology is deeply intertwined with education and learning strategies. Stimulating learning through comprehensive educational programmes is essential for fostering the knowledge and skills required to innovate and implement biofuel solutions effectively. This section explores

various educational strategies crucial for promoting biofuel technology.

Curriculum Development and Training Programmes

Curriculum development in the field of biofuels must be multifaceted, integrating diverse aspects such as biology, chemistry, environmental science, and engineering. At the university level, specialised courses focusing on biofuel production processes, feedstock management, and sustainability assessments are necessary. These courses should not only provide theoretical knowledge but also include practical components like laboratory work and industry placements to offer hands-on experience (Swetha *et al.*, 2021). For professionals already in the energy sector, training programmes are crucial for updating their skills and knowledge. These programmes could cover advanced topics in biofuel technology, including the latest research developments, technological innovations, and environmental impact assessments (Colmenares *et al.*, 2020). Online courses and workshops can also be effective in reaching a broader audience, providing flexible learning opportunities for continuous professional development.

Case Studies of Successful Educational Initiatives in Biofuel Technology

Several educational initiatives around the world have successfully contributed to the advancement of biofuel technologies. For instance, in the United States, universities such as Arizona State University, University of California, and Iowa State University have partnered with biofuel companies like BP Technology Ventures, Chevron Technology Ventures, and ConocoPhillips Company for research and development projects (Washburn & Jennifer, 2010). These collaborations have provided students with practical experience in cutting-edge biofuel technologies while contributing to significant technological advancements. Over a span of 10 years, these partnerships have led to more than 55 university-industry alliances, worth an estimated $1.3 billion to $2.2 billion, resulting in commercial-scale applications of biofuel innovations.

In China, a study on the effectiveness of "learning by doing" in advanced biofuels demonstrated that production costs could potentially be reduced by up to 70% between 2015 and 2035, depending on learning rates (Chen *et al*., 2012). There are also vocational training programmes designed to prepare technicians for work in biofuel production facilities, emphasising the practical skills needed in this industry (Kirshner *et al.*, 2022). Another approach can be found in community outreach programmes in rural areas, where local populations are educated on producing and utilising biofuels from local biomass resources (Ymeri *et al.*, 2020). These programmes often focus on simple, scalable technologies suitable for small-scale production, providing communities with both education and a means to generate sustainable energy.

Integrating Stimulating Learning Approaches in Biofuel Education

Integrating stimulating learning approaches in biofuel education across various educational levels is key to developing a comprehensive understanding of biofuel technologies. At the primary and secondary school levels, an introduction to fundamental concepts of renewable energy and sustainability can establish a strong foundation for future educational pursuits (Nida *et al.*, 2021). This early exposure is pivotal in cultivating a foundational awareness among young learners. At the university level, more specialised and in-depth courses are essential for training the next generation of scientists, engineers, and policy makers in the field of biofuels (Kamusoko *et al*., 2021; Eshiemogie *et al*., 2022). Such educational offerings need to delve into the complexities of biofuel technologies, covering both theoretical aspects and practical applications.

Simultaneously, professional training programmes are essential to address the continuous learning needs of those already engaged in or transitioning into the biofuel

industry. These training initiatives should be dynamically structured to align with the latest advancements and innovations in the biofuel field, ensuring that the current workforce remains proficient and skilled (Colmenares *et al*., 2020; Bisognin *et al*., 2024). By adopting a comprehensive educational strategy for biofuels, covering everything from basic learning to advanced professional training, a strong foundation can be built. This approach benefits learners at all educational levels. This strategic stimulating learning approach is critical in endowing individuals with the essential knowledge and competencies necessary to make substantive contributions to both the progression and practical application of sustainable biofuel technologies.

Biotechnology in Biofuel Education

The integration of biotechnological principles within biofuel education is fundamental for the progression of sustainable fuel alternatives. Biotechnology is instrumental in enhancing, refining, and amplifying the processes involved in biofuel production, notably within the spheres of second and third-generation biofuels (Kumar *et al.*, 2022; Cardoso *et al.*, 2023). This subsection examines the crucial facets of integrating biotechnology within the educational infrastructure for biofuel technology. Biotechnology stands as a key driver in enhancing the production efficiency and environmental sustainability of biofuels. Specifically, within the field of second-generation biofuels, the advancements in biotechnology are essential for devising effective strategies to decompose lignocellulose biomass into fermentable sugar (Guimarães *et al.*, 2023; Shakir *et al.*, 2023c). This process involves the application and refinement of enzymes and microorganisms, techniques honed through biotechnological advancements. Figure 5 illustrates the biotechnological approaches involved in enhancing biofuel development, showcasing key components such as genetic engineering, cultivation methods, and the extraction technique.

In the context of third-generation biofuels, biotechnology unlocks opportunities for delving into the realm of algal biofuels. Given their notable lipid content and swift growth rates, algae are considered a highly promising resource for biofuel production. Biotechnological education in this domain should involve

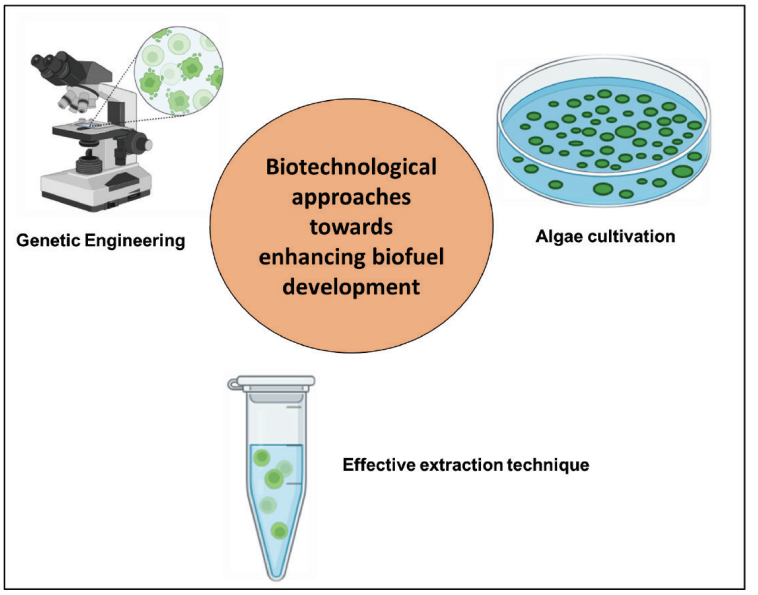

Figure 5: An illustration of biotechnological approaches in biofuel development

instruction in genetic engineering to boost lipid yields, knowledge about cultivating algae, and techniques for effective extraction (Rafa *et al.*, 2021; Powar *et al.*, 2022). Embedding biotechnology within the biofuel educational spectrum demands an interdisciplinary strategy. Curriculum development must encompass a diverse range of subjects, including but not limited to molecular biology, genetic engineering, microbiology, and biochemistry, as well as fields such as process engineering and bioreactor design (Alanazi, 2023; Figueiredo *et al.*, 2023). To foster practical skills, it is essential to incorporate laboratory work and research initiatives within the curriculum, providing tangible, hands-on experience in biotechnological methods, and their application in the context of biofuel production. This comprehensive approach is key to equipping students with a well-rounded educational experience, blending theoretical knowledge with practical expertise.

Additionally, considering the rapid pace of progress in biotechnological research, it is crucial for professionals in the field to engage in continuous learning and professional development. Accessible learning platforms like workshops, seminars, and online courses are key to keeping professionals well-informed about the latest advancements and trends in biofuel biotechnology (Kaur & Bhaskar, 2020; Kumar *et al.*, 2023). It is also important for educational initiatives to address the broader picture, including the ethical, environmental, and economic aspects of applying biotechnology in biofuel production. This means gaining a clear understanding of regulations around Genetically Modified Organisms (GMO), assessing the environmental impacts of biotechnological processes and evaluating the economic viability of these technologies (Pryshliak & Tokarchuk, 2020; Moshood *et al.*, 2021). In summary, biotechnology is a key driver in the evolution of biofuel technologies, and its integration into biofuel education is imperative. By equipping students and professionals with comprehensive knowledge and practical skills in biotechnological applications, the biofuel sector can achieve greater strides in developing sustainable and efficient biofuel solutions.

Socioeconomic Implications of Educated Biofuel Development

The development of biofuels, underpinned by a strong foundation in education and knowledge has significant socioeconomic implications. Implementing a stimulating learning approach to biofuel production that is informed by education allows for diverse benefits, encompassing economic expansion, job generation, skill development, and social progress. The comprehensive impact of biofuel development aligns with the objectives of SDG 8 (Decent Work and Economic Growth), contributing not just to new job and industry creation but also promoting sustainable economic advancement and diversification within the labour force (Nazari *et al.*, 2021). Educated biofuel development ensures that the workforce is equipped with the skills to thrive in this ever-evolving sector, stimulating innovation and increasing production efficiency. This is essential for achieving the objectives of SDG 7 (Affordable and Clean Energy), advocating for the advancement and use of renewable energy sources to make sustainable energy more widespread and dependable (Kang *et al.*, 2023).

Additionally, a knowledge-centric methodology in biofuel production substantially aids in achieving SDG 13 (Climate Action) (García *et al.*, 2021) by the environmentally responsible production of biofuels. This approach helps mitigate the impacts of climate change, reduces greenhouse gas emissions and promotes the adoption of more sustainable agricultural methods.

Moreover, incorporating biofuels into the broader energy framework offers a viable alternative to fossil fuels and plays a significant role in spurring rural development. This integration bolsters local economies and opens up new avenues for social progress. These benefits align with the Sustainable Development Goals (SDGs), which emphasise environmental

sustainability alongside economic and social inclusiveness. In essence, the pursuit of educated biofuel development is a strategic approach to achieving a harmonious balance between sustainable energy, economic growth, and social advancement. As the biofuel industry continues to mature, its contribution to these global objectives becomes increasingly pivotal. This underscores the critical role of education and a deep-rooted knowledge base in propelling this vital sector of sustainable development forward.

The Impact of Knowledge-Driven Biofuel Production on Economies

The transition towards biofuel production that is driven by advanced knowledge and innovation is key to transforming economies, particularly in regions abundant in biomass. This shift in biofuel production methods spurred by educational developments and innovative technologies not only makes the production of biofuels more efficient and sustainable but also significantly reduces the environmental impact of these fuels (Kugele & Sarkar, 2023). Efficient and sustainable biofuel production can lower costs and enhance its competitiveness in the energy market. This increased market appeal leads to investment and stimulates growth in the biofuel sector, positively affecting the broader economy (Hasan *et al.*, 2023).

Additionally, shifting to domestically produced biofuels reduces dependence on imported fossil fuels, thereby enhancing energy security, balancing trade deficits, and strengthening national economies (Millinger *et al.*, 2022). This change brings economic benefits and helps reduce global greenhouse gas emissions, a vital step in addressing climate change challenges. Furthermore, diversifying energy sources with biofuels contributes to the stabilisation of energy prices, benefiting both consumers and business (Usmani *et al.*, 2023). This stability is crucial in providing affordable and sustainable energy solutions.

In conclusion, the role of knowledge-driven biofuel production is vital to both economic growth and the worldwide effort to combat climate change. By advancing sustainable and efficient biofuel technologies, considerable economic and climate change-reducing advantages are attainable. Consequently, the growth of the biofuel industry represents not only an economic pursuit but also a critical element in the global initiative to establish a more sustainable and eco-friendly energy future.

Job Creation, Skill Development, and Social Advancement

The biofuel sector is labour intensive and has the capacity for significant job creation throughout its entire supply chain, encompassing activities from biomass cultivation and harvesting to its processing and distribution. The spectrum of job opportunities within this sector ranges from positions requiring minimal skill to those demanding high levels of specialisation, thereby nurturing a workforce of varied expertise (Ramos *et al.*, 2022). This diversity is pivotal to encourage continuous, inclusive, and sustainable economic growth along with productive employment and decent work for all. With the expansion of the biofuel industry, there is an escalating demand for professionals skilled in diverse facets of biofuel technology, fostering an environment conducive to skill development and career advancement (Karp *et al.*, 2021). The educational and training frameworks required for these jobs play a critical role in enhancing the skill sets of the workforce, thereby improving employability and potentially increasing income levels (Usmani *et al.*, 2023). This aspect of skill development is particularly impactful in rural regions, where biofuel production introduces new opportunities, thereby aiding in the rejuvenation of local economies.

Furthermore, the jobs created through the expansion of the biofuel industry substantially contributes to societal progress, especially for underrepresented and marginalised groups. This furthers social inclusion and equity, ensuring a wide distribution of the benefits emanating from the burgeoning biofuel sector and aiding in the reduction of societal disparities (Mahmood *et al*., 2023). Providing these communities with

access to education, training, and employment within the biofuel domain has a pronounced effect on social upliftment and empowerment. In summary, the evolution of the biofuel industry not only addresses the requirements for sustainable energy solutions but also plays an instrumental role in the creation of jobs, development of skills, and the promotion of social equity. These efforts are integral in realising several of the United Nations Sustainable Development Goals, especially those centred on economic growth, employment, and the reduction of inequalities.

Challenges and Opportunities in Biofuel Education

Stimulating learning in biofuel education is pivotal for the advancement of sustainable energy solutions, yet a unique set of challenges and opportunities confronts it. Effectively tackling these challenges and capitalising on these opportunities are essential for nurturing a workforce that can significantly advance and drive the biofuel sector. A primary challenge in biofuel education is staying abreast with swift technological developments and understanding the intricate relationship between biofuels and various dimensions such as environmental impact, economic considerations, and social factors (Subramaniam & Masron, 2021; Hoang *et al.*, 2023). This necessitates an educational approach that is both interdisciplinary and adaptable to ongoing changes. It is vital to bridge the existing gap between academic curriculum and the real-time requirements of the dynamically changing biofuel industry to prepare a workforce capable of addressing these industry needs.

Conversely, the prospects in biofuel education are considerable, especially with the increasing global emphasis on sustainable energy. This shift presents educational institutions with the opportunity to be frontrunners in this field through dedicated programmes, research endeavours, and partnerships with the industry (Duarah *et al.*, 2023). Such initiatives can offer students practical experiences, thereby enriching their educational journey with real-world relevance and impact. The growth of online educational and training platforms is a notable opportunity to make biofuel education more universally accessible (Paudel, 2021). This plays a crucial role in forming an informed community that recognises the significance and possibilities of sustainable energy solutions. Additionally, integrating biofuel education into policy development is imperative to ensure informed and effective policies that support sustainable energy growth (Gradziuk *et al.*, 2021). This aspect is particularly important as it promotes economic growth, supports the creation of quality jobs, and fosters an innovative and sustainable industrial sector.

Conclusions

The exploration and development of biofuels as a sustainable energy option underscore the need to integrate stimulating learning approaches within educational frameworks. Education is foundational in progressing the field of biofuels, from grasping basic biofuel technologies to comprehending the complex socioeconomic impacts. This review underscores the significance of stimulating learning at various levels, including academic programmes, professional training, and public awareness campaigns to spur innovation and adoption in the biofuel sector. Stimulating learning approaches in biofuel technologies not only equips individuals with essential skills and knowledge but also propels the industry through research and development. The multi-disciplinary character of biofuel education, integrating aspects of environmental science, engineering, and policy studies, equips learners to tackle the diverse challenges in this sector.

Additionally, an informed approach to developing biofuels has significant implications for economies and societies, aiding in enhancing employment, economic diversification, and environmental sustainability. Looking ahead, the field of biofuel development presents both challenges and opportunities, with education playing a pivotal role in navigating them.

Updating educational programmes to align with rapid technological progress remains a key challenge. Collaborative efforts among educational institutions, industry sectors, and governments will be instrumental in advancing biofuel education. Last but not least, the advancement of sustainable biofuel development depends significantly on the capacity to educate and train a new generation of professionals, researchers, and policymakers. Stimulating learning in this field is crucial to harnessing the full potential of biofuels as a key component of a sustainable energy portfolio. Progressing forward, it is imperative to continually adapt, innovate, and learn about the role of biofuel in achieving a more sustainable and greener future.

Acknowledgements

The authors would like to thank the International Centre for Genetic Engineering and Biotechnology (ICGEB), Grant Number of 304. PTEKIND.6501382.I151 (R504-LR-GAL008-0006501382-I151) for funding this study.

Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefits, commercial, or financial conflicts and declare absence of conflicting interests with the funders.

References

Afeyan, N. B., & Cooney, C. L. (2020). Professor Daniel IC Wang: A legacy of education, innovation, publication, and leadership. *Biotechnology and Bioengineering*, *117*(12), 3615.

Alagumalai, A., Mathimani, T., Pugazhendhi, A., Atabani, A., Brindhadevi, K., & Canh, N. D. (2020). Experimental insight into co-combustion characteristics of oxygenated biofuels in modified DICI engine. *Fuel*, *278*, 118303.

Alam, M. S., & Tanveer, M. S. (2020). Conversion of biomass into biofuel: A cutting-edge technology. *Bioreactors*, 55-74.

Alanazi, F. H. (2023). Saudi students' and science teachers' knowledge of and attitudes towards biotechnology. *Journal of Biological Education*, *57*(1), 196-213.

Alizadeh, R., Lund, P. D., & Soltanisehat, L. (2020). Outlook on biofuels in future studies: A systematic literature review. *Renewable and Sustainable Energy Reviews*, *134*, 110326.

Ambaye, T. G., Vaccari, M., Bonilla-Petriciolet, A., Prasad, S., Hullebusch, V.E. D., & Rtimi, S. (2021). Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives. *Journal of Environmental Management*, *290*, 112627. https://doi.org/10.1016/j.jenvman.2021.112627

Amerit, B., Ntayi, J. M., Ngoma, M., Bashir, H., Echegu, S., & Nantongo, M. (2023). Commercialization of biofuel products: A systematic literature review. *Renewable Energy Focus*, *44*, 223-236. https://doi.org/10.1016/j.ref.2022.12.008

Armstrong, J. H. (2021). People and power: Expanding the role and scale of public engagement in energy transitions. *Energy Research & Social Science*, *78*, 102136.

Anto, S., Mukherjee, S. S., Muthappa, R., Mathimani, T., Deviram, G., Kumar, S. S., & Pugazhendhi, A. (2020). Algae as green energy reserve: Technological outlook on biofuel production. *Chemosphere*, *242*, 125079.

Beig, B., Riaz, M., Naqvi, S. R., Hassan, M., Zheng, Z., Karimi, K., & Chi, N. T. L. (2021). Current challenges and innovative developments in pretreatment of lignocellulosic residues for biofuel production: A review. *Fuel*, *287*, 119670.

Bharathiraja, B., Iyyappan, J., Gopinath, M., Jayamuthunagai, J., & PraveenKumar, R. (2022). Transgenicism in algae: Challenges in compatibility, global scenario and future prospects for next generation biofuel production. *Renewable and Sustainable Energy Reviews*, *154*, 111829.

Bhatia, L., Sarangi, P. K., Singh, A. K., Prakash, A., & Shadangi, K. P. (2022). Lignocellulosic waste biomass for biohydrogen production: Future challenges and bio-economic perspectives. *Biofuels, Bioproducts and Biorefining*, *16*(3), 838-858.

Bisognin, G. T., de Souza Savian, F., Duarte Ribeiro, J. L., & Mairesse Siluk, J. C. (2024). Unlocking Brazil's green hydrogen potential: Overcoming barriers and formulating strategies to this promising sector. *International Journal of Hydrogen Energy*, *49*, 553-570. https://doi.org/10.1016/j.ijhydene.2023.09.227

Blanchard, M. R., Venditti, R. A., McAlexander, S. L., McCance, K. R., & Collier, K. M. (2021). An interdisciplinary model to diversify STEM participation: College, high school, and industry partnerships enhancing learning opportunities through student, scientist, and teacher partnerships. In Farland-Smith, D. (Ed.), *Enhancing learning opportunities through student, scientist and teacher partnerships* (pp. 95-132). IGI Global.

Cardoso, L. O. B., Procópio, D. P., Borrego, B. B., Gracioso, L. H., Stevani, C. V., Freire, R. S., do Nascimento, C. A. O., & Perpetuo, E. A. (2023). Overview of CO2 bioconversion into third-generation (3G) bioethanol—a patent-based scenario. *Bioenergy Research*, *16*(3), 1229-1245.

Carrino, L., Visconti, D., Fiorentino, N., & Fagnano, M. (2020). Biofuel production with castor bean: A win–win strategy for marginal land. *Agronomy*, *10*(11), 1690.

Chen, X., Khanna, M., & Yeh, S. (2012). Stimulating learning-by-doing in advanced biofuels: Effectiveness of alternative policies. *Environmental Research Letters*, *7*(4), 045907.

Colmenares-Quintero, R. F., Rico-Cruz, C. J., Stansfield, K. E., & Colmenares-Quintero, J. C. (2020). Assessment of biofuels production in Colombia. *Cogent Engineering*, *7*(1), 1740041.

Deora, P. S., Verma, Y., Muhal, R. A., Goswami, C., & Singh, T. (2022). Biofuels: An alternative to conventional fuel and energy source. *Materials Today: Proceedings*, 48, 1178-1184.

Dishadewi, P., Wiyarsi, A., Prodjosantoso, A., & Nugraheni, A. (2020). Chemistry-based socio-scientific issues (SSis) as a learning context: An exploration study of biofuels. *Journal of Physics: Conference Series*, *1440*, 012007.

Duarah, P., Haldar, D., & Purkait, M. K. (2023). Policies of biofuel for commercialization. In Shah, M. P. (Ed.), *Green approach to alternative fuel for a sustainable future* (pp. 1-11). Elsevier.

Ebadian, M., Dyk, V.S., McMillan, J. D., & Saddler, J. (2020). Biofuels policies that have encouraged their production and use: An international perspective. *Energy Policy*, *147*, 111906.

Eshiemogie, S. O., Ighalo, J. O., & Banji, T. I. (2022). Knowledge, perception and awareness of renewable energy by engineering students in Nigeria: A need for the undergraduate engineering program adjustment. *Cleaner Engineering and Technology*, *6*, 100388.

Esmaeili, S. A. H., Sobhani, A., Szmerekovsky, J., Dybing, A., & Pourhashem, G. (2020). First-generation vs. second-generation: A market incentives analysis for bioethanol supply chains with carbon policies. *Applied Energy*, *277*, 115606.

Estevez, R., Aguado-Deblas, L., López-Tenllado, F. J., Luna, C., Calero, J., Romero, A. A., & Luna, D. (2022). Biodiesel is dead: Long life to advanced biofuels—a comprehensive critical review. *Energies*, *15*(9), 3173. https://doi.org/10.3390/en15093173

Figueiredo, M., Dias, A., Neves, J., & Vicente, H. (2023). Assessment of literacy to biotechnological solutions for

environmental sustainability in Portugal. *Sustainability*, *15*(13), 10056.

Ganguly, P., Sarkhel, R., & Das, P. (2021). The second-and third-generation biofuel technologies: Comparative perspectives. *Sustainable Fuel Technologies Handbook*, 29-50.

García-Franco, A., Godoy, P., de la Torre, J., Duque, E., & Ramos, J. L. (2021). United Nations sustainability development goals approached from the side of the biological production of fuels. *Microbial Biotechnology*, *14*(5), 1871.

Gradziuk, P., Jończyk, K., Gradziuk, B., Wojciechowska, A., Trocewicz, A., & Wysokiński, M. (2021). An economic assessment of the impact on agriculture of the proposed changes in EU biofuel policy mechanisms. *Energies*, *14*(21), 6982.

Grangeia, C., Santos, L., & Lazaro, L. L. B. (2022). The Brazilian biofuel policy (RenovaBio) and its uncertainties: An assessment of technical, socioeconomic and institutional aspects. *Energy Conversion and Management: X*, *13*, 100156.

Guddaraddi, A., Singh, A., Amrutha, G., Saikanth, D., Kurmi, R., Singh, G., & Singh, B. V. (2023). Sustainable biofuel production from agricultural residues an eco-friendly approach: A review. *International Journal of Environment and Climate Change*, *13*(10), 2905-2914.

Guimarães, C. E. C., Neto, F. S., de Castro Bizerra, V., do Nascimento, J. G. A., Valério, R. B. R., de Sousa Junior, P. G., & De Lima, R. K. C. (2023). Sustainable bioethanol production from first-and second-generation sugar-based feedstocks: Advanced bibliometric analysis. *Bioresource Technology Reports*, *23*, 101543.

Hanna, R., Heptonstall, P., & Gross, R. (2024). Job creation in a low carbon transition to renewables and energy efficiency: A review of international evidence. *Sustainability Science*, *19*(1), 125-150

Hasan, M., Abedin, M. Z., Amin, M. B., Nekmahmud, M., & Oláh, J. (2023). Sustainable biofuel economy: A mapping through bibliometric research. *Journal of Environmental Management*, *336*, 117644.

Hoang, A. T., Sirohi, R., Pandey, A., Nižetić, S., Lam, S. S., Chen, W.-H., & Pham, V. V. (2023). Biofuel production from microalgae: Challenges and chances. *Phytochemistry Reviews*, *22*(4), 1089-1126.

Kamusoko, R., Jingura, R. M., Parawira, W., & Chikwambi, Z. (2021). Strategies for valorization of crop residues into biofuels and other value-added products. *Biofuels, Bioproducts and Biorefining*, *15*(6), 1950-1964.

Kang, H., Li, G., & Gao, J. (2023). Development of bio-diesel to achieve Sustainable Development Goal 7. *Frontiers in Energy Research*, *10*, 1057336.

Karp, S. G., Medina, J. D., Letti, L. A., Woiciechowski, A. L., de Carvalho, J. C., Schmitt, C. C., de Oleveira Penha, R., Kumlehn, G. S., & Soccol, C. R. (2021). Bioeconomy and biofuels: The case of sugarcane ethanol in Brazil. *Biofuels, Bioproducts and Biorefining*, *15*(3), 899-912.

Kaur, R., & Bhaskar, T. (2020). Potential of castor plant (*Ricinus communis*) for production of biofuels, chemicals, and value-added products. In Bhaskar, T., Pandey, A., Rene, E. R., & Tsang, D. C. W. (Eds.), *Waste biorefinery* (pp. 269-310). Elsevier.

Kirshner, J., Brown, E., Dunlop, L., Cairo, J. P. F., Redeker, K., Veneu, F., & Walton, P. H. (2022). "A future beyond sugar": Examining second-generation biofuel pathways in Alagoas, northeast Brazil. *Environmental Development*, *44*, 100739. https://doi.org/10.1016/j.envdev.2022.100739

Kotsis, K. T. (2024). Promoting scientific literacy by teaching in primary education the issue of "biomass for biodiesel". *European Journal of Contemporary Education and E-Learning*, *2*(5), 63-76.

Kugele, A. S. H., & Sarkar, B. (2023). Reducing carbon emissions of a multi-stage smart production for biofuel towards sustainable development. *Alexandria Engineering Journal*, *70*, 93-113.

Kumar, P., Singh, B., Patwardhan, S. B., Dwivedi, S., Sarkar, S., Roy, A., & Pandit, S. (2022). Brief introduction to first, second, and third generation of biofuels. In Chowdhary, P., Khanna, N., Pandit, S., Kumar, R. (Eds.), *Bio-clean energy technologies: Volume 1* (pp. 1-29). Springer.

Kumar, T., Basakran, G. K., Marsuki, M. Z., Wash, A. M., Mohsin, R., Majid, Z. A., & Ghafir, M. F. A. (2023). Exploring socioeconomic and political feasibility of aviation biofuel production and usage in Malaysia: A thematic analysis approach using expert opinion from aviation industry. *Green Energy and Intelligent Transportation*, *2*(5), 100111.

Leibensperger, C., Yang, P., Zhao, Q., Wei, S., & Cai, X. (2021). The synergy between stakeholders for cellulosic biofuel development: Perspectives, opportunities, and barriers. *Renewable and Sustainable Energy Reviews*, *137*, 110613.

Levine, I. A., Gerk, C. L., Gómez, S. M., Nalley, J. O., & Nalley, M. M. (2021). The algae foundation® and algae technology educational consortium. *Journal of the World Aquaculture Society*, *52*(5), 1099-1117.

Lin, C.-Y., & Lu, C. (2021). Development perspectives of promising lignocellulose feedstocks for production of advanced generation biofuels: A review. *Renewable and Sustainable Energy Reviews*, *136*, 110445.

Mahmood, T., Hussain, N., Shahbaz, A., Mulla, S. I., Iqbal, H. M., & Bilal, M. (2023). Sustainable production of biofuels from the algae-derived biomass. *Bioprocess and Biosystems Engineering*, *46*(8), 1077-1097.

Malode, S. J., Prabhu, K. K., Mascarenhas, R. J., Shetti, N. P., & Aminabhavi, T. M. (2021). Recent advances and viability in biofuel production. *Energy Conversion and Management: X*, *10*, 100070. https://doi.org/10.1016/j.ecmx.2020.100070

Mat Aron, N. S., Khoo, K. S., Chew, K. W., Show, P. L., Chen, W. H., & Nguyen, T. H. P. (2020). Sustainability of the four generations of biofuels–a review. *International Journal of Energy Research*, *44*(12), 9266-9282.

Millinger, M., Reichenberg, L., Hedenus, F., Berndes, G., Zeyen, E., & Brown, T. (2022). Are biofuel mandates cost-effective?-An analysis of transport fuels and biomass usage to achieve emissions targets in the European energy system. *Applied Energy*, *326*, 120016.

Morone, P., Cottoni, L., & Giudice, F. (2023). Biofuels: Technology, economics, and policy issues. In Luque, R., Lin, C. S. K., Wilson, K., & Du, C. (Eds.), *Handbook of biofuels production* (pp. 55-92). Woodhead Publishing.

Moshood, T. D., Nawanir, G., & Mahmud, F. (2021). Microalgae biofuels production: A systematic review on socioeconomic prospects of microalgae biofuels and policy implications. *Environmental Challenges*, *5*, 100207.

Müller, C., Scapini, T., Rempel, A., Abaide, E. R., Camargo, A. F., Nazari, M. T., & Zabot, G. L. (2023). Challenges and opportunities for third-generation ethanol production: A critical review. *Engineering Microbiology*, *3*(1), 100056.

Narwane, V. S., Yadav, V. S., Raut, R. D., Narkhede, B. E., & Gardas, B. B. (2021). Sustainable development challenges of the biofuel industry in India based on integrated MCDM approach. *Renewable Energy*, *164*, 298-309.

Nazari, M. T., Mazutti, J., Basso, L. G., Colla, L. M., & Brandli, L. (2021). Biofuels and

their connections with the sustainable development goals: A bibliometric and systematic review. *Environment, Development and Sustainability*, *23*(8), 11139-11156.

Neupane, D. (2023). Biofuels from renewable sources, a potential option for biodiesel production. *Bioengineering*, *10*(1), 29. https://doi.org/10.3390/bioengineering10010029

Nida, S., Marsuki, M. F., & Eilks, I. (2021). Palm-oil-based biodiesel in Indonesia: A case study on a socioscientific issue that engages students to learn chemistry and its impact on society. *Journal of Chemical Education*, *98*(8), 2536-2548.

Pabbathi, N. P. P., Velidandi, A., Tavarna, T., Gupta, S., Raj, R. S., Gandam, P. K., & Baadhe, R. R. (2021). Role of metagenomics in prospecting novel endoglucanases, accentuating functional metagenomics approach in second-generation biofuel production: A review. *Biomass Conversion and Biorefinery*, *13*(2), 1371-1398. https://doi.org/10.1007/s13399-020-01186-y

Pascoli, D. U., Aui, A., Frank, J., Therasme, O., Dixon, K., Gustafson, R., & Wright, M. M. (2022). The US bioeconomy at the intersection of technology, policy, and education. *Biofuels, Bioproducts and Biorefining*, *16*(1), 9-26.

Patel, A., & Shah, A. R. (2021). Integrated lignocellulosic biorefinery: Gateway for production of second generation ethanol and value added products. *Journal of Bioresources and Bioproducts*, *6*(2), 108-128.

Patwardhan, S. B., Pandit, S., Ghosh, D., Dhar, D. W., Banerjee, S., Joshi, S., & Ruokolainen, J. (2022). A concise review on the cultivation of microalgal biofilms for biofuel feedstock production. *Biomass Conversion and Biorefinery*, 1-18.

Paudel, P. (2021). Online education: Benefits, challenges and strategies during and after COVID-19 in higher education. *International Journal on Studies in Education (IJonSE)*, *3*(2).

Perea-Moreno, M.-A., Manzano-Agugliaro, F., Hernandez-Escobedo, Q., & Perea-Moreno, A.-J. (2020). Sustainable thermal energy generation at universities by using loquat seeds as biofuel. *Sustainability*, *12*(5), 2093.

Postal, A. M., Benatti, G., Palmeros Parada, M., Asveld, L., Osseweijer, P., & Da Silveira, J. M. F. (2020). The role of participation in the responsible innovation framework for biofuels projects: Can it be assessed? *Sustainability*, *12*(24), 10581.

Powar, R. S., Yadav, A. S., Ramakrishna, C. S., Patel, S., Mohan, M., Sakharwade, S. G., & Sharma, A. (2022). Algae: A potential feedstock for third generation biofuel. *Materials Today: Proceedings*, *63*, A27-A33.

Pryshliak, N., & Tokarchuk, D. (2020). Socio-economic and environmental benefits of biofuel production development from agricultural waste in Ukraine. *Environmental & Socio-economic Studies*, *8*(1), 18-27.

Rafa, N., Ahmed, S. F., Badruddin, I. A., Mofijur, M., & Kamangar, S. (2021). Strategies to produce cost-effective third-generation biofuel from microalgae. *Frontiers in Energy Research*, *9*, 749968.

Ramos, J. L., Pakuts, B., Godoy, P., García-Franco, A., & Duque, E. (2022). Addressing the energy crisis: Using microbes to make biofuels. *Microbial Biotechnology*, *15*, 1026-1030.

Rosales-Asensio, E., Segredo-Morales, E., Gómez-Marín, N., Pulido-Alonso, A., & Sierra, C. (2023). A techno-economic appraisal of green diesel generation through hydrothermal liquefaction, leveraging residual resources from seaweed and fishing sectors. *Water*, *15*(17), 3061.

Sadatshojaei, E., Wood, D. A., & Mowla, D. (2020). Third generation of biofuels

exploiting microalgae. *Sustainable Green Chemical Processes and their Allied Applications*, 575-588.

Saini, R., Osorio-Gonzalez, C. S., Brar, S. K., & Kwong, R. (2021). A critical insight into the development, regulation and future prospects of biofuels in Canada. *Bioengineered*, *12*(2), 9847-9859.

Saratale, R. G., Ponnusamy, V. K., Jeyakumar, R. B., Sirohi, R., Piechota, G., Shobana, S., & Shin, H. S. (2022). Microalgae cultivation strategies using cost–effective nutrient sources: Recent updates and progress towards biofuel production. *Bioresource Technology*, *361*, 127691.

Shakir, M. A., Ahmad, M. I., Ramli, N. K., Yusup, Y., Alosaimi, A. M., Alorfi, H. S., & Rafatullah, M. (2023). Review on the influencing factors towards improving properties of composite insulation panel made of natural waste fibers for building application. *Journal of Industrial Textiles*, *53*, 1-33.

Shakir, M. A., Ahmad, M. I., Yusup, Y., & Rafatullah, M. (2023a). From waste to wealth: converting rubber wood sawdust into green mycelium-based composite. *Biomass Conversion and Biorefinery*, *15*, 739-757. https://doi.org/10.1007/s13399-023-05113-9

Shakir, M. A., Ahmad, M. I., Yusup, Y., Wabaidur, S. M., Siddiqui, M. R., Alam, M., & Rafatullah, M. (2023b). Effect of fibrillation degree of empty fruit bunch fiber on sandwich composite incorporate with spent mushroom substrate. *Journal of Industrial Textiles*, *53*.

Shakir, M. A., Ahmad, M. I., Yusup, Y., Wabaidur, S. M., Siddiqui, M. R., Alam, M., & Rafatullah, M. (2023c). Sandwich composite panel from spent mushroom substrate fiber and empty fruit bunch fiber for potential green thermal insulation. *Buildings*, *13*(1), 224.

Sharmila, V. G., Banu, J. R., Kumar, M. D., Kumar, S. A., & Kumar, G. (2022). Algal biorefinery towards decarbonization: Economic and environmental consideration. *Bioresource Technology*, *364*, 128103.

Subramaniam, Y., & Masron, T. A. (2021). The impact of economic globalization on biofuel in developing countries. *Energy Conversion and Management: X*, *10*, 100064.

Swetha, A., ShriVigneshwar, S., Gopinath, K. P., Sivaramakrishnan, R., Shanmuganathan, R., & Arun, J. (2021). Review on hydrothermal liquefaction aqueous phase as a valuable resource for biofuels, bio-hydrogen and valuable bio-chemicals recovery. *Chemosphere*, *283*, 131248.

Tudge, S. J., Purvis, A., & De Palma, A. (2021). The impacts of biofuel crops on local biodiversity: A global synthesis. *Biodiversity and Conservation*, *30*(11), 2863-2883.

Usmani, R. A., Mohammad, A. S., & Ansari, S. S. (2023). Comprehensive biofuel policy analysis framework: A novel approach evaluating the policy influences. *Renewable and Sustainable Energy Reviews*, *183*, 113403.

Vickram, S., Manikandan, S., Deena, S., Mundike, J., Subbaiya, R., Karmegam, N., & Ravindran, B. (2023). Advanced biofuel production, policy and technological implementation of nano-additives for sustainable environmental management–A critical review. *Bioresource Technology*, *387*, 129660.

Voca, N., & Ribic, B. (2020). Biofuel production and utilization through smart and sustainable biowaste management. *Journal of Cleaner Production*, *259*, 120742.

Washburn, J. (2010). *Big oil goes to college*. Center for American Progress.

Wong, K. H., Tan, I. S., Foo, H. C. Y., Chin, L. M., Cheah, J. R. N., Sia, J. K., Tong, K. T.

X., & Lam, M. K. (2022). Third-generation bioethanol and L-lactic acid production from red macroalgae cellulosic residue: Prospects of Industry 5.0 algae. *Energy Conversion and Management*, *253*, 115155.

Ymeri, P., Gyuricza, C., & Fogarassy, C. (2020). Farmers' attitudes towards the use of biomass as renewable energy—A case study from southeastern europe. *Sustainability*, *12*(10), 4009.

Yusoff, M. N. A. M., Zulkifli, N. W. M., Sukiman, N. L., Chyuan, O. H., Hassan, M. H., Hasnul, M. H., Zulkifli, M. S. A., Abbas, M. M., & Zakaria, M. Z. (2021). Sustainability of palm biodiesel in transportation: A review on biofuel standard, policy and international collaboration between Malaysia and Colombia. *Bioenergy Research*, *14*, 43-60.

Zilberman, D., Reardon, T., Silver, J., Lu, L., & Heiman, A. (2022). From the laboratory to the consumer: Innovation, supply chain, and adoption with applications to natural resources. *Proceedings of the National Academy of Sciences*, *119*(23), e2115880119.