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Review Article

Biofuels: Exploring the Future of Green & Clean Energy

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Abstract Biofuels; a potential and renewable solution to climate change, fossil fuel depletion, and energy security. 1st, 2nd, 3rd, and 4th generation biofuels are the main types of biofuels widely used worldwide, have different feedstock, production methods, and environmental impacts. 1st generation biofuels including ethanol and biodiesel, produced from food crops like sugar-cane, corn, and vegetable oil, are extensively used but have prompted concerns about land use and food availability. 2nd generation biofuels including cellulosic ethanol and bio-oils that mainly produced from fuel crops, agricultural wastes and forest byproducts by using enzymatic hydrolysis and thermochemical processes; are not only more ecofriendly but mitigate food-fuel conflict. On the other hand, 3rd generation biofuels derived from algae have advantage due to easy availability and high oil-content. 4th generation biofuels are supposed to be next-generation fuels due to modified technologies and innovative methods, use microbes, waste CO_2 and other byproducts into high-energy fuels, significantly reducing greenhouse gas emissions and enhancing overall efficiency. Biofuels are renewable with carbon neutrality, reduce environmental pollution, minimize green-house gas emission, enhance energy security, stimulate economic growth, creating job opportunities, promoting rural development, minimizing water pollution as well as deforestation and beneficial for eco-systems. Except these benefits biofuels have some obstacles that hinder their efficiency like land degradation, underprivileged government policies, lack of people awareness, low energy return on investment, high production costs, unsafe production methods, limited feedstock and land utilization. Besides these challenges, biofuels are still a sustainable energy source that mitigate climate change and satisfy global energy demand.

Keywords: Biofuel, Green energy, Biodiesel, Sustainable future, EROI.

1. INTRODUCTION

Energy availability issues , fossil fuel depletion and climate change are altering the global energy landscape [1, 2]. These interconnected challenges are driving profound changes in energy production and consumption, paving the way for a more sustainable and resilient future [3]. Among these, climate change is the most critical issue, with fossil fuels being the major source of emissions of greenhouse gases [4]. The adverse effects of global warming are elevating sea levels, extreme climate change, and environmental disturbances are the main issues world is facing today [5]. Simultaneously, depletion of fossil fuel is increasing [6] and natural (finite) energy resources like natural gas, petroleum, coal and oil are no longer sustainable [7]. As readily available reserves diminish, the ecological and economic costs of extraction increase, highlighting an urgent demand for renewable energy alternatives to ensure sustainable energy availability [8].

Energy security is a growing concern, especially for nations heavily reliant on imported fossil fuels, which exposes them to geopolitical risks, supply disruptions, and volatile energy prices [9]. To protect national security and ensure economic stability, it is essential to diversify energy sources and boost domestic production. With the increasing global energy demand, the establishment of dependable, clean, and self-sustaining energy systems has become critically necessary [10]. The shift to sustainable energy alternatives, such as biofuels and other renewable resources, is essential for mitigating emissions, reducing reliance on fossil fuels, and improving energy security [11]. Achieving this transition will require groundbreaking technological advancements and international collaboration to create a more resilient and sustainable global energy system [12].

Biofuels offer an effective and alternative solution to the latest issues world is facing including, waste management, energy security, minimize climate change, fossil-fuel depletion, and reduce green-house gases [13]. Biofuels, originating from renewable organic sources including plants, algae, and garbage, can be produced locally, reducing reliance on imported fossil fuels [14]. They provide a more environmentally friendly option compared to existing energy sources, [12, 15, 16], potentially reducing greenhouse gas emissions and alleviating the ecological consequences of conventional fuels [17]. As the world moves toward a greener energy future, biofuels are becoming increasingly crucial [18]. Advancements in technology are pushing biofuels beyond traditional first-generation sources like ethanol from food crops, second- and third-generation biofuels made from non-food biomass and algae are proving to be more sustainable, reducing the competition between food and fuel while boosting fuel yields and enhancing environmental benefits [19]. Biofuels are expected to play a central role in creating a cleaner, more secure energy future as the world works to meet climate goals and reduce fossil fuel dependency [20].

This review investigates the various categories of biofuels, analyzing their benefits, challenges, and potential role in the ongoing global energy transition. From first-generation biofuels to third-generation, we will assess their contribution to tackling climate change, fossil fuel depletion, and energy security. The benefits, such as lower greenhouse gas emissions and energy diversification, will be balanced against obstacles such as land use competition and production costs. Furthermore, we will look into future technology breakthroughs that could improve biofuels' contribution to a sustainable and safe global energy system.

2. TYPES OF BIOFUELS

Biofuels are mainly categorized into three types (first, second, and third generations), each having unique benefits and challenges in tackling global energy needs [21]. First-generation biofuels are derived from food crops such as sugarcane, corn and vegetable oils, offering a commonly known and available alternative to fossil fuels [22]. However, they face challenges for competing with food production, raising concerns about food security [23]. Second-generation biofuels, mainly produced from non-food biomass like forestry waste, agricultural wastes non-food crops, or lingo-cellulosic crops), provide a more sustainable alternative by avoiding food supply problems. However, their manufacturing procedures are complex [24]. Third-generation biofuels generated from algae promise improved sustainability through higher oil yields and reduced land utilization [25]. Fourth-generation biofuels are derived from genetically modified (GM) microorganism using advanced methods and technologies. But they are still in the testing stage, dealing with some sustainability and economic issues [26]. As biofuels establish comprehending their various forms and possibilities is essential for evaluating their impact on addressing climate change, decreasing reliance on fossil-fuels, and improving energy availability.

2.1. First-Generation Biofuels

First-generation biofuels originate from edible crops [27] containing high levels of starch, sugars, or oils, which makes them suitable for energy conversion [22]. Important feedstock comprises corn, sugarcane, and various vegetable oils including canola, soybean and palm oil [28]. In countries such as the USA, corn serves as the primary raw material for ethanol production [29], whereas in Brazil, sugarcane stands as the leading feedstock [30], that produce both electricity and ethanol via cogeneration and fermentation [31]. Vegetable oils undergo a transformation into biodiesel, alternative to conventional diesel due to eco-friendly nature [32]. The availability of these crops, coupled with the existing agricultural infrastructure, facilitates large-scale processing with relative ease. However, the utilization of edible crops for production of biofuels has raised issues regarding environmental sustainability and food security [33], except this 80-90% of total biofuel is supposed to be 1st generation biofuel. Ethanol [34] and biodiesel [35] are most common 1st generation biofuel**.**

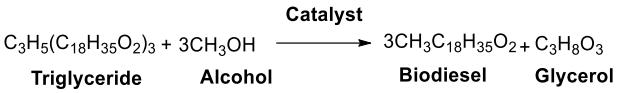
- **Ethanol**: Produced through the fermentation of sugar-rich crops like corn and sugarcane [36], ethanol is mainly used as an additive in gasoline (e.g., E10, E15, or E85) or as a standalone fuel (E100) in flexible fuel vehicles [37, 38].
- **Biodiesel**: Biodiesel is synthesized via transesterification, wherein animal fats or vegetable oils e.g., soybean-oil, canola-oil and palm-oil react with alcohol (methanol or ethanol), yielding biodiesel and glycerol as byproducts [39]. Biodiesel either in its pure form or mixed with conventional diesel (petroleum-based) in different proportions (e.g., B20 or B100), offering a more eco-friendly alternative to traditional diesel [40].

The essential technologies for production of 1st generation biofuel are

- **Fermentation (Ethanol Production)**: The biochemical process eq. 1, where glucose or starch in crops (like sugarcane or corn) by the action of yeast transformed into ethanol and CO_2 [41]. The produced ethanol used as a fuel after purification or distillation [42].

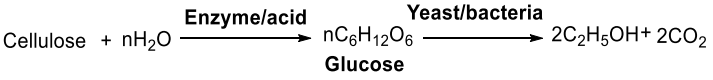
$$\underset{\text{Glucose}}{C_6H_{12}O_6} \xrightarrow{\text{yeast}} \underset{\text{Ethanol}}{2C_2H_5OH} + 2CO_2 \quad (1)$$

- **Transesterification (Biodiesel Production)**: In transesterification equation.2, triglycerides (oils or fats) react in the presence of catalyst (acid or base) and alcohol (ethanol/methanol) to produce biodiesel and glycerol [43]. This step produced high yield biofuel with high purity as compared to other methods [44].



(2)

- **Hydrolysis (Ethanol from Cellulose)**: Cellulose or hemicellulose from plant are converted into glucose either by using cellulase enzyme (enzymatic hydrolysis) [45] or dilute acid (acidic hydrolysis) [46], afterward fermented into ethanol and carbon dioxide via yeast [47] or bacteria [48] equation 3..

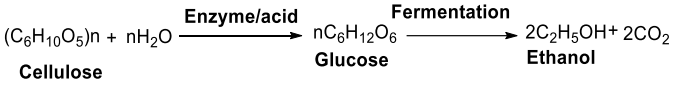


(3)

2.2. Second-Generation Biofuels

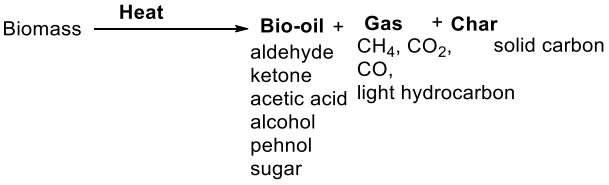
Non-food biomass used to produce 2nd generation biofuels [49], including crop residue (corn stover, wheat straw, rice husks), and forestry waste (sawdust, wood chips) [50]. Dedicate energy crops (poplar, willow, miscanthus, and switch-grass) can also serve as feedstock [51]. These materials don't compete with food crops due to their easy availability, addressing one of the major concerns associated with first-generation biofuels. 2nd generation biofuels provide a more environmentally friendly and sustainable option to food-based biofuels by using non-edible plant material and agricultural waste [52]. Furthermore, energy-crops can be cultivated on marginal lands (lands with poor climate or unable to cultivate crops), reducing pressure on food production areas. 10-15% world's biofuel belongs to 2nd generation biofuel. Most prominent second-generation biofuels are cellulosic ethanol [53] and bio-oils [54].

- **Cellulosic-Ethanol:** Cellulosic-ethanol is a next-generation biofuel made from the **non-food parts of plants** (agricultural waste, wood, and energy crops) [55]. Unlike traditional ethanol, which uses sugar and starch, it is derived from complex macromolecules like cellulose, pectin, lignin and hemicellulose present in plant's cell wall [56]. The process (eq. 4) is more complex, requiring the breakdown of tough plant fibers into fermentable sugars. However, it offers **higher energy yields per acre** and is more sustainable since it doesn't compete with food-crops and makes use of materials that would otherwise go to waste [57]. This makes it a promising solution for both reducing dependence on fossil fuels and addressing environmental concerns [58].



(4)

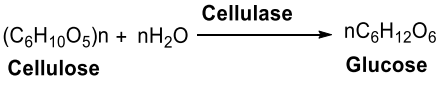
- **Bio-Oils:** Bio-oils are produced from plant oils or biomass using thermo-chemical processes (eq. 5) like pyrolysis or hydrothermal liquefaction [59]. These can replace diesel fuel or be further processed into biofuels through refining or catalytic processing. These oils, derived from non-food biomass, are versatile, with applications ranging from transportation fuels to industrial feedstock [60].



(5)

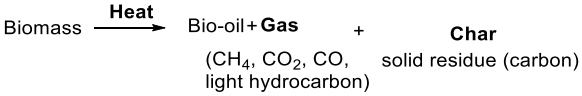
Significant Technologies for Producing Second-generation biofuels are

- **Enzymatic Hydrolysis:** A critical technology for producing cellulosic ethanol, enzymatic hydrolysis involves using enzymes like cellulase to break down cellulose into simpler sugars (glucose) eq. 6, further fermented to produce ethanol [61, 62]. This method is more energy-efficient than other techniques but requires optimization to increase yield and reduce costs [63]. Due to complex nature of cellulose, some pretreatments (acid hydrolysis or steam explosion) are often employed to enhance the accessibility of cellulose to the enzymes [64].



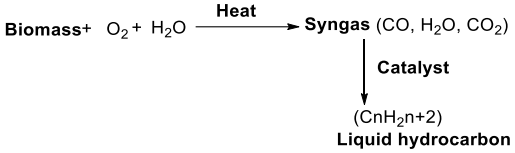
(6)

- **Thermochemical Processes:** Thermochemical conversion technologies, including liquefaction (conversion of liquid from solid or gas), pyrolysis (heating biomass in the absence of oxygen), hydrothermal liquefaction (conversion of biomass into crude oil at high temperature and pressure) and gasification (conversion of biomass into syngas), are commonly used to create bio-oils and other biofuels from non-food biomass under high temperature [65] or in absence of oxygen [66].
- **Pyrolysis (eq. 7)** rapidly heats biomass without oxygen, producing bio-oil, gas (methane, carbon monoxide, carbon dioxide and some light hydrocarbons), and char. This process is scalable and efficient, making it ideal for converting a wide range of raw material, including forestry and agricultural waste [67].



(7)

- **Gasification (eq. 8)** converts biomass into syngas (a mixture of carbon dioxide, hydrogen, and carbon monoxide), which can then be turned into liquid biofuels through Fischer-Tropsch synthesis (FTS) or other catalytic methods where Fe, Co, Ru and Ni complexes used as catalysts [68].



(8)

- **Hydrothermal Liquefaction (eq. 9)** is the natural formation of fossil fuels, using high pressure and temperature to convert wet biomass into bio-oil [69].

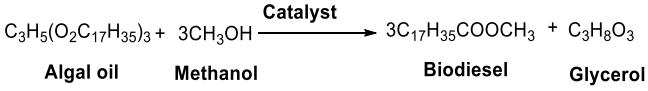


(9)

2.3. Third-Generation Biofuels

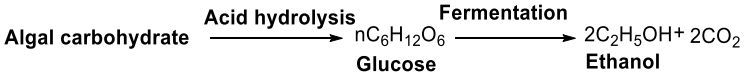
Third-generation biofuels are derived from algae, an exceptional feedstock for biofuel production due to its rapid growth, high lipid content, and ability to thrive in a variety of environments [70]. Unlike conventional biofuel sources, algae don't require arable land or fresh water, making them a sustainable alternative [71]. Algae (micro-algae, macro-algae) and seaweeds can be cultivated in freshwater, brackish water, or even wastewater, offering a versatile solution to biofuel production [72, 73]. Rich in oils, carbohydrates, and proteins, algae can be used to produce algal biodiesel and bioethanol, making it an attractive option for reducing food crop competition and minimizing land use concerns typically associated with first and second-generation biofuels [74]. According to a rough estimation only 1% biofuel belong to this generation. Algal biodiesel [75] and algal bioethanol [76] are two main types of third generation biofuels.

- **Algal Biodiesel**: Algal biodiesel (equation 10), derived by extracting oils (lipids) from algae, bacteria or yeast and converting them through transesterification, presents a promising alternative to fossil fuels [77]. Some algae species are capable of producing up to 50% of their dry weight in lipids, a yield far surpassing that of traditional oilseed crops like soybean or palm [78]. These oils can then be refined into biodiesel, providing a sustainable, environmentally friendly substitute for diesel, with potential applications in both transportation and industrial sectors [79].



(10)

- **Bioethanol**: Algae can also be converted into bioethanol (equation 11) by fermenting the carbohydrates present in algae (such as starches or sugars) using microorganisms like yeast [80]. Algal species like Chlorella and Spirulina, known for their high carbohydrate content, are ideal for production by acid hydrolysis or fermentation [81]. Unlike traditional bioethanol derived from food crops like corn, algal bioethanol avoids the food-versus-fuel dilemma, making it a sustainable biofuel option [82].



(11)

One of the most compelling environmental advantages of third-generation biofuels from algae is their ability to absorb carbon dioxide (CO_2) during growth [83]. Algae, as photosynthetic organisms, capture CO_2 from the atmosphere and convert it into biomass using sunlight [84]. This natural process helps mitigate the impact of greenhouse gas emissions by effectively removing CO_2 from the air [85, 86].

The cultivation of algae for biofuels can serve as a carbon sink, making algae-based biofuels a potentially carbon-neutral or even carbon-negative energy source, depending on production and transportation processes [87]. Algae are particularly efficient at CO_2 capture, absorbing more CO_2 per unit area than land-based plants [88]. Additionally, algae can be cultivated using wastewater or non-potable water, further reducing the environmental impact [89]. This approach not only reduces freshwater consumption but also remove excess nutrients like phosphorus and nitrogen from wastewater, which are often pollutants in agricultural and industrial run off [90].

Graphical comparison between 1st, 2nd and 3rd type of biofuels is summarized below

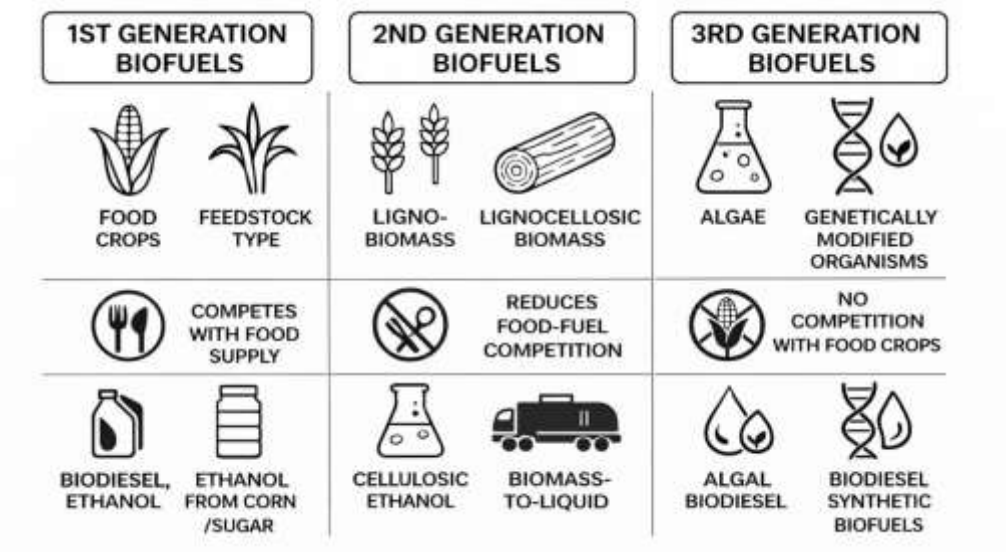


Figure 1: Comparison between 1st, 2nd, 3rd & 4th type of biofuels for better underdtanding.

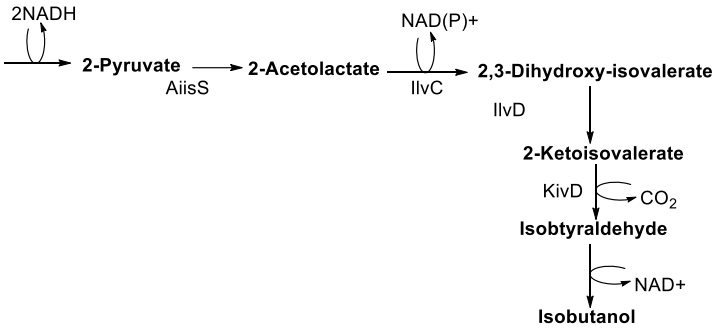
2.4. 4th Generation Biofuels (Next-generation biofuels)

As, biofuel's consumption is increasing dramatically with an increase of population and life style. Today, we need some better biofuel as compared to 1st, 2nd, 3rd generations due to some disadvantages. These generations effect the climate change as well. To overcome this issue, a new concept of next-generation biofuels was given around 2008 known as 4th generation biofuels [91]. Percentage production of 4th generation is less than 1% because it is in still under experimental level but results are outstanding with zero carbon emission that indicate it will be the future biofuel [92, 93]. The main feedstock included genetically engineered microorganism like cyanobacteria, *E. coli,* yeast, modified algae strains, flue gases, CO_2 from atmosphere, waste CO_2 [94]. Most prominent 4th generation biofuels are

- **Isobutanol:** mainly produced from engineered *E. coli, yeast, Clostridium acetobutylicum, Bacillus subtilis, Clostridium beijerinkckii, Pseudomonas putida,* and *Saccharomyces cerevisiae via aerobic or anaerobic fermentation* [95]. Isobutanol have high energy density with low volatility as compared to ethanol and better as gasoline substitute [96]
- **Fatty acid ethyl esters (FAEE):** produced from *E. coli* or modified with TesA, AccD6, WS/DGAT [97]. This type can be used in diesel engines as an alternative to commercial biodiesel, with high efficiency and less toxicity [98].
- **Hydrogen gas:** used in hydrogen fuel cells and can be produced via photobiological water splitting and can be prepared from GM algae with improved hydrogenase [99, 100].
- **Propane:** engineered E. coli or modified algae are the main source for propane, that can be used in cooking, heating purposes [101].
- **Alkanes:** produced from GM cyanobacteria normally used as jet or diesel fuel [102].
- **Ethanol via microbial electro-synthesis:** microorganisms like acetogens in the presence of carbon dioxide and electricity, produced ethanol that can be used as blended biofuel [103].

Main technologies for production of 4th generation biofuels included

- **Synthetic biology:** GM yeast, *cyanobacteria, E. coli* produce fuel molecules. Synthetic gene circuits are inserted to the microorganism that convert CO2 or sugars into lipids, hydrocarbons or alcohols (equation 12).
- **CRISPR technology:** by using gene editing tool, DNA in living organism can be insert, delete or modified to control gene expression and eliminate unwanted metabolic function [104] like cyanobacteria used for lactate production [105]. *Synechocystis* can be modified by this technology for direct alkane secretion [106], *Chlamydomonas* used for hydrogen production [107]
- **Metabolic engineering:** In metabolic engineering, cellular pathways can be optimized through gene modification to increase yield as well as efficiency of fuel. These modified pathways redirect carbon flux towards fuel reduction [108].
- **CCU (carbon capture and utilization):** GM autotropic microbes or photosynthetic algae capture CO_2 from air or fuel gas and convert into hydrocarbons or alcohols [109].
- **PBR (photobioreactor) system:** under controlled or closed environments algae or cyanobacteria optimize light and CO_2 to produce hydrocarbon (equation 13) that reduce pollution [110].



(12)

$$CO_2 + H_2O + \text{light} \xrightarrow{\textit{GM cyanobacteria}} \text{hydrocarbon} + O_2 \quad (13)$$

- **Microbial electro-synthesis:** microbes use electrons (electricity) to reduce CO_2 into biofuel [111] or in ethanol, butanol, methane, acetic acid [112] (equation 14). Like *Clostridium ljungahlii* produce ethanol [113], *Acetobacterium woodii*- actic acid [114], *Methanogenes*-methane [115], *Acetognes*-acetates [116].

$$2CO_2 + 8H^+ + 8e^- \xrightarrow{\textit{acetogens}} CH_3COOH + 2H_2O \quad (14)$$

- **Photobiological system:** some GM microorganisms like *cyanobacteria* direct convert CO_2 and sunlight into liquid fuel [117] (equation 15).

$$CO_2 + H_2O + \text{light} \xrightarrow{\textit{GM cyanobacteria}} \text{Heptane} + O_2 \quad (15)$$

3. ADVANTAGES OF BIOFUELS

Biofuels offering innovative solutions to some of the world's most pressing challenges, including economic growth, energy security, and climate change [118]. Their widespread adoption across diverse sectors is driving sustainability and reducing our dependence on finite fossil resources. In transportation, biodiesel and biofuels are key players in cutting carbon emissions, facilitating a cleaner, greener future.

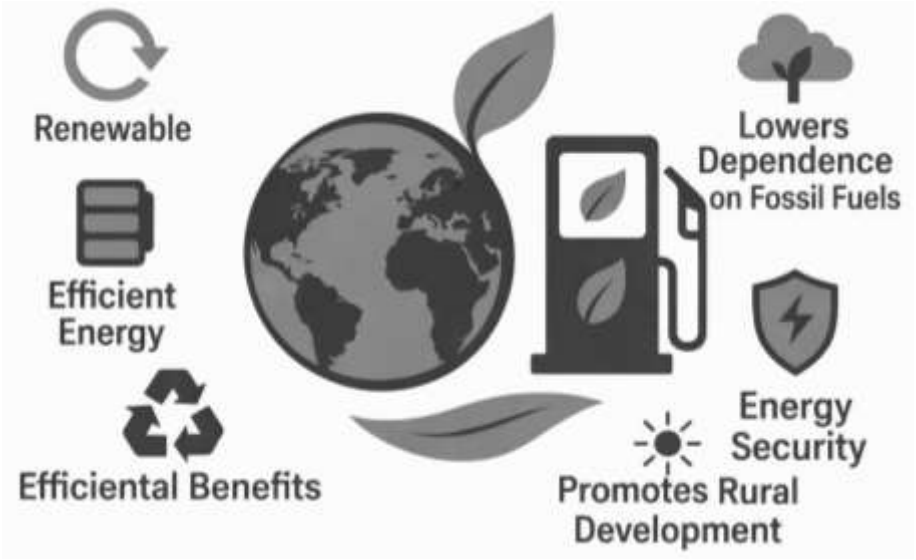


Figure 2. Some general advantages of biofuels like energy security, renewability, energy efficiency, dependency and promotion of rural development.

Table 1: A brief comparison between 1st, 2nd, 3rd & 4th generation biofuels

Aspect	*1st Generation*	*2nd Generation*	*3rd Generation*	*4th Generation*
Feedstock	Food crops e.g., corn, sugarcane, wheat, vegetable oil	Non-food biomass e.g., agricultural waste, wood, grass	Algae	GM microorganism e.g., E. coli, cyanobacteria, yeast, algae, waste CO_2
Technology	Fermentation Transesterification Hydrolysis	Enzymatic hydrolysis Thermochemical process Pyrolysis Gasification Hydrothermal liquefaction	Catalytic transesterification Acid hydrolysis, fermentation	Synthetic biology Metabolic engineering CRISPR CCU Photobioreactor Microbial electrosynthesis Photobiological system
Production Cost	Low	Higher than 1st gen	High (due to algae cultivation costs)	Very high (experimental, needs R&D investment)
Advantages	Well established Quick production Support rural economy	Doesn't compete with food Produced from waste mater More sustainable	High yield Can absorb carbon dioxide Grows on non-arable land	Carbon-negative potential Highly efficient Sustainable
Disadvantages	Deforestation Require high water Require fertilizers	Complex processing High cost	Expensive technologies Not widely commercialized Controlled conditions required	Still in R&D phase Complex process Controlled conditions
Environmental Impact	Moderate	Lower than 1st gen	Lower CO_2 footprint can be carbon-neutral	Potentially carbon-negative Sustainable Reduce pollution
Examples	Ethanol Biodiesel	Cellulosic ethanol Bio-oil Bio-butanol Light hydrocarbons Biogas	Algal biodiesel Bio-hydrogen Bioethanol	Isobutanol Propane Alkane hydrogen gas FAEE Ethanol

3.1. Carbon-Neutrality

Biofuels are regarded as carbon-neutral because the CO_2 emitted during their combustion is approximately equal to the CO_2 absorbed by the plants during their growth [119]. Through photosynthesis, biofuel crops capture carbon dioxide from the atmosphere. When burned, the carbon they store is released back into the atmosphere, completing the carbon cycle [120]. In contrast, burning fossil fuels releases carbon that has been trapped underground for millions of years, leading to a net increase in atmospheric CO_2 [121]. However, the carbon neutrality of biofuels relies on the entire production process, cultivation, harvesting, transportation, and conversion. If any stage is inefficient or dependent on fossil fuels, the reduction in CO_2 emissions may be less impactful [122].

3.2. Sustainable-Future

Countries with limited fossil fuel reserves often rely heavily on oil imports, leaving them vulnerable to price fluctuations, geopolitical conflicts, and supply disruptions. Biofuels offer a promising alternative, as they can be locally produced from agricultural, forestry, or waste materials [123, 124]. In African countries like South Africa, Nigeria, Tanzania, Ethiopia etc., are increasingly turning to biofuels to improve their energy security, with biofuels contributing up to 9-14% [125]. By adopting biofuels, these nations could significantly reduce reliance on imported oil, enhancing energy sovereignty and stability. For instance, biofuels like ethanol and biodiesel can effectively replace petroleum-based fuels, decreasing the need for oil imports and fostering greater energy independence [126].

3.2. Diversified-Energy-Mix

Biofuels are essential in creating a more varied and sustainable energy mix, crucial for long-term energy security [127]. By incorporating biofuels alongside renewable energy sources such as wind, solar, and natural gas, countries can decrease their reliance on any single energy type. This diversification enhances energy resilience, making systems more robust against global market fluctuations, political instability, and natural disasters. It also strengthens energy reliability as global trends continue to evolve [128, 129].

3.3. Boosting Job Opportunities in Rural Communities

The production of biofuels, especially from crops such as corn, sugarcane, and oilseeds, creates numerous employment opportunities in rural regions. These occupations encompass agriculture, feedstock processing, transportation, and biofuel plant operations, yielding a substantial economic enhancement for local communities. In addition to direct employment, the biofuel

sector fosters economic expansion by creating new markets for agricultural commodities, revitalizing farming-dependent communities, and ensuring sustained prosperity [130, 131].

3.4. Promoting-Economic-Growth

The biofuel sector possesses significant potential to boost the economy by energizing the bio-economy. With rising worldwide demand for renewable energy, governments investing in biofuels may secure a competitive advantage in the international market. This facilitates the export of biofuel technologies, feedstock, and finished products, generating additional revenue [11, 132, 133].

3.5. Renewability & Long-Term-Sustainability

Biofuels are naturally renewable, in contrast to fossil fuels, that are limited and take countless years to develop. They are made from biological resources that can be regenerated seasonally or annually, including waste products, plants, and vegetable oils [134]. Biofuels can be produced annually from crops like corn, sugarcane, and oilseeds, and they can even be obtained from waste cooking oil [135, 136]. Algae also provide a very sustainable biofuel because they can be grown easily all over the world [137, 138]. We won't experience the same depletion issues as we do with fossil fuels because biofuels are renewable, assuring a steady and sustainable energy source [13].

Biofuels constitute a significantly more sustainable energy alternative compared to fossil fuels, especially when generated using sustainable approaches [139]. The environmental impact of biofuel production can be significantly mitigated by cultivating feedstock on marginal lands, [140, 141], , recycling waste biomass [142] , or producing algae [143]. Improvements in sustainable farming methods guarantee that biofuels can achieve carbon neutrality or perhaps carbon negativity, rendering them a feasible long-term energy solution [144]. Furthermore, innovations in waste-to-energy technology, including the conversion of agricultural leftovers and food waste into biofuels, are advancing sustainability significantly [145]. These technologies offer a renewable energy source while simultaneously minimizing waste, reducing greenhouse gas emissions, and aiding in environmental conservation [146]. This comprehensive strategy renders biofuels an effective instrument for addressing our energy requirements while protecting our planet for future generations [147, 148].

4. CHALLENGES OF BIOFUELS

Biofuels present considerable potential; yet, they also introduce numerous challenges that must be meticulously handled to guarantee their long-term sustainability. Some basic challenges are discussed in this review.



Figure 3. Key challenges of Biofuel production & sustainability.

4.1. Food Production Competition

Many biofuels, including ethanol made from maize and biodiesel made from soybean or palm oil, require a large amount of land to produce [149]. Consequently, there is direct competition between food crops and biofuel crops [150, 151]. When food prices rise due to fewer crops being available, food insecurity may worsen, especially in poor countries [150, 152, 153]. This problem is especially common in areas where small-scale farmers rely on agricultural land for their livelihood [154].

4.2. Deforestation, Land degradation and Habitat loss

The expansion of biofuel crops, especially in tropical regions for palm oil production, has contributed to deforestation [155], which increases carbon emissions by destroying vital carbon sinks such as rainforests and threatens biodiversity [156]. Large-scale deforestation, often driven by the cultivation of biofuel crops such as palm oil, leads to the destruction of habitats, endangering species like tigers and orangutans [157] in countries like Indonesia and Brazil [158, 159]. Furthermore, changes in land use contribute to climate change by releasing stored carbon from trees and soil into the atmosphere, exacerbating the problem [160-162].

4.3. Pollution and Water Consumption

Biofuel crops, especially in arid regions, require substantial amounts of water for irrigation [163, 164]. For example, maize, used for ethanol production, places significant pressure on local water resources [165]. Additionally, runoff from fertilizers and pesticides used in biofuel crop cultivation can pollute nearby water supplies [166-168].

4.4. Net Energy Balance and Carbon Footprint

The entire process of producing, harvesting, processing, and transporting biofuels requires significant energy inputs [169]. In some cases, biofuels are less efficient than fossil fuels because the energy required to produce them can be nearly equal to or even exceed the energy they generate [16].

While biofuels are often considered "carbon neutral," this may not always be true due to the energy required for their production and processing [11]. Additionally, carbon emissions from deforestation can significantly offset the environmental benefits of biofuels if forests are cleared to grow biofuel crops [170].

4.5. Production Costs and Government Policies

The production of biofuels can be more expensive than that of fossil fuels, especially when oil prices are low [171]. Although the cost of producing biofuels has been decreasing, the complexity of their production and the need for subsidies to remain competitive mean that they are often still more costly than fossil fuels [172].

Government policies and international agreements are crucial drivers in the growth and competitiveness of biofuels [173]. As biofuel production requires significant investment in infrastructure, research, and development, governments play a key role in making biofuels economically viable through subsidies, tax incentives, and grants [174, 175]. For example, the U.S. allocated around $3.5 billion for renewable energy projects in 2020, while Brazil's Proálcool Program helped the country reach 31 billion liters of ethanol production in 2020 [176]. Policies like blending mandates, such as the Renewable Fuel Standard (RFS) in the U.S. and the Renewable Energy Directive (RED) in the EU [177], ensure a stable market by requiring biofuels to be mixed with traditional fuels, incentivizing innovation and further investment in biofuel technologies [178]. International agreements, particularly the Paris Agreement, have bolstered biofuels as carbon-neutral alternatives to fossil fuels, supporting global climate goals and encouraging cross-border collaboration [179, 180]. Additionally, trade policies like the EU-Mercosur trade agreement work to reduce tariffs and open new markets, expanding biofuel trade opportunities and fostering global industry growth with GDP approximately $20 trillion [181]. In essence, government actions and international cooperation create the necessary conditions for biofuels to thrive, helping them become an integral part of the global transition to renewable energy [182, 183].

4.6. Energy Return on Investment (EROI)

EROI is an essential measure for assessing the efficiency of energy sources [184]. It compares the energy produced by a source to the energy required to extract or produce it. Simply, EROI indicates how much energy we receive from a fuel in relation to the energy we invest in obtaining it, giving us a clear understanding of its real energy value [185].

Normally, biofuels have low EROI but depends on various factors like feedstock and production process [186] as compared to fossil fuels [187]. Bioethanol produced by maize has 1.6 EROI in Indonesia and bioethanol produced by sugarcane has 21 [188], but normally bioethanol from sugarcane: 1.796, corn: 1.040 and wood: 0.739 [189]. Biogas generally has highest EROI 1.24-11.05 [186] but depends on feedstock available like biogas produced by solid waste material like manure exhibited 3.7 (dairy cattle) and 14.7 (chicken) [190], from crop residue ranges 5.1–10.8 (triticale residue) to 15.7–17.0 (corn residue) [191]. Biodiesel relatively low EROI, synthesized by vegetable oil (4.85D5.88) [192], Soybean oil (0.78-4.56) [193], sunflower oil (0.76-4.5) [194, 195] and rapeseed oil (1.05-3.71) [196].

On the other hand, oil exhibited EROI ranges 20-41 [197], natural gas: 10 [198], coal: 95 [199], nuclear: 90 [200], hydropower: 110 [201], solar: 0.7-3.1 [202], wind: 6.5-57.6 [203]. A higher EROI indicates the energy is cost-effective, more efficient and easy to extract [204] while a lower value indicates energy is consumed to produce the fuel than its generates [205].

5. FUTURE PROSPECTS OF BIOFUELS

With the help of new technologies and encouraging government policies, biofuels have a bright future [206]. According to the IEA (International Energy Agency), by 2030, biofuels will make up 5-10% of the world's energy mix, mainly because different countries are trying to reduce their carbon footprints in transportation and industry [11, 207]. The sustainability of 2nd generation and 3rd generation biofuels can be enhanced, as they can be produced from agricultural waste and algae [208]. Additionally, biofuels in the aviation sector could be key to reducing emissions, IATA (International Air Transport Association) projecting that SAF (sustainable aviation fuels) that could contribute up to 65% of the industry's decarbonization efforts by 2050. [209]. The U.S. Department of Energy estimates that second-generation biofuels could reduce lifecycle greenhouse gas emissions by up to 90% compared to conventional gasoline [210]. However, World Bank reports that biofuels production could cause land-use changes that lead to deforestation, increasing carbon emissions [211]. Furthermore, biofuels are still economically less competitive than fossil fuels, though research is steadily reducing production costs [212]. With ongoing technological innovations and stronger policy frameworks, biofuels are expected to play an essential role in a low-carbon future, although their success will depend on overcoming these environmental and economic hurdles [213].

5.1. Technological Innovations and Catalyst Development

As the global demand for sustainable energy solutions intensifies, biofuels have surfaced as a formidable alternative to conventional fossil fuels [214]. Derived from organic sources such as plants, algae, and waste, biofuels offer a cleaner, renewable energy solution that not only helps reduce greenhouse gas emissions but also lessens our dependence on finite, non-

renewable resources [215]. Recent breakthroughs in biofuel technology have greatly enhanced production efficiency, scalability, and sustainability, positioning biofuels as a competitive and viable option alongside traditional fossil fuels [216].

Catalyst play an important role in biodiesel production, as they facilitate the chemical reaction responsible for conversion of oil/fat into biodiesel [217]. Previously, inorganic catalysts like NaOH, CaOH, ZnO, CaO, KOH, and some metal complexes were widely used [218]. However, modification in the industry have been prompted the investigations to organic catalysts as alternatives. These organic catalysts like hydrazone, imidazole, organic amines, cellulose derivatives show better performance in addition to low toxicity and high environmental impact [219]. This shift from traditional catalysts to advanced catalysts will enhance the production of biodiesel [220].

5.2. Transforming waste material into Biofuel

Biofuels, produced by the conversion of waste materials into energy, are gradually becoming a sustainable substitute for fossil fuels [221]. In 2022, the United States, the largest producer of biofuels, produced biodiesel (3.1 billion gallons) as well as ethanol (15.4 billion gallon) [222]. Similarly, countries like Finland, Brazil, Sweden and Denmark, in 2022, produced 30% of their total energy by using bioenergy [223]. Olive-stones, a byproduct during olive oil production in Spain is effectively used as source of biomass for biofuel production for decarburization and reduce heating costs [224]. In 2022, Denmark is planning to produce 100% biomethane into gas in 2040 mainly produced from waste material [225].

5.3. Genetically-Engineered-Crops

Genetic engineering is revolutionizing the development of biofuel feedstock [226], enabling crops that use fewer resources such as land, water, and fertilizer while yielding higher outputs [227]. Researchers are focused on creating genetically modified crops with enhanced disease resistance, drought tolerance, and increased oil content, all of which can improve the efficiency of biofuels [228, 229]. Innovations are also targeting plants with higher cellulosic content such as hybrid switchgrass making them more suitable for 2nd generation biofuels especially in USA [230]. These advances can make biofuels more competitive with fossil fuels by increasing energy yields and reducing cultivation costs [231].

5.4. New Feedstock and Advanced Processing Techniques

Today, biofuel production depends on food crops, the future is moving toward using non-food biomass, waste materials, and even algae as feedstock due to high consumption of biofuels [232]. Cellulosic biofuels, derived from agricultural leftovers, forest waste, or purpose-grown energy crops, are gaining traction as a sustainable solution [233]. Unlike first-generation biofuels, this feedstock doesn't compete with food production, easing concerns around the "food vs. fuel" debate. New technologies for the conversion of cellulose into fermentable sugars are improving the commercial viability of cellulosic ethanol. Meanwhile, algal biofuels [234], produced from algae that can grow on non-arable land or even in wastewater, hold incredible promise [235]. Algae's high oil content and rapid growth rate offer the potential for high yields with minimal environmental impact, making algae-based biofuels [236], a game-changer for sustainability and scalability [237].

Concurrently, advanced processing technologies are streamlining biofuel production and cutting down on energy consumption [238]. Techniques such as thermochemical conversion (including pyrolysis and gasification) enable more efficient transformation of biomass into liquid biofuels and bio-oils [239-241]. Meanwhile, enzymatic hydrolysis of cellulosic materials and direct fermentation of non-food sugars are advancing rapidly, allowing for more efficient conversion of diverse feedstock into biofuels [242].

These technological breakthroughs in feedstock diversity and processing efficiency hold the potential to significantly reduce biofuel production costs and improve the energy return on investment (EROI), making biofuels more competitive with fossil fuels [243]. Additionally, integrating sustainable farming practices and waste-to-biofuel technologies like converting agricultural or industrial waste into fuel will optimize resource use and support the transition to a circular economy [244].

6. CONCLUSION

Biofuels are a versatile and adaptable solution to climate change, fossil fuel depletion, and energy security. This study covered first-generation biofuels produced from food crops and second- and third-generation biofuels generated from non-food waste and algae, which are more ecologically friendly. While 4th generation biofuels are more sustainable, zero carbon emission and eco-friendlier as compared to others, produced from genetically modified microorganisms. Each category has advantages in material kinds, environmental impact, and technology readiness. Land usage, economic viability, and environmental impacts remain issues. Biofuels offer several advantages despite these issues. They can reduce greenhouse gas emissions, protect energy, boost economic growth, and enable a sustainable energy future. New advanced biofuel technologies including waste-to-energy processes and algal biofuels make biofuels more probable to help clean energy transition. Biofuels can't attain their full potential without government initiatives, investment, and international cooperation. Biofuels will remain an essential element of the world's energy mix as long as authorities stimulate their production, stabilize markets through mixing rules, and promote international collaboration. As governments and companies invest more in R&D, biofuels will help fulfill energy needs and combat climate change. Despite their flaws, biofuels are crucial to a more sustainable energy economy.

With better technology, sensible legislation, and continued research, biofuels can help future generations become carbon-neutral and energy-secure.

Authors' Contributions

In this study, authors contributed equally to the study.

Conflicts of Interest

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

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