

Review

First-Generation Biofuels vs. Energy Security: An Overview of Biodiesel and Bioethanol

Renata Marks-Bielska ¹, Stanisław Bielski ^{2,*}, Krystyna Kurowska ³ and Anna Zielińska-Chmielewska ⁴

¹ Faculty of Economic Sciences, University of Warmia and Mazury in Olsztyn, Oczapowskiego 4, 10-719 Olsztyn, Poland; renatam@uwm.edu.pl

² Faculty of Agriculture and Forestry, University of Warmia and Mazury in Olsztyn, Oczapowskiego 8, 10-719 Olsztyn, Poland

³ Faculty of Geoengineering, University of Warmia and Mazury in Olsztyn, Prawocheńskiego 15, 10-724 Olsztyn, Poland; krystyna.kurowska@uwm.edu.pl

⁴ Institute of Economics, Poznań University of Economics and Business, Al. Niepodległości 10, 61-875 Poznań, Poland; anna.zielinska@ue.poznan.pl

* Correspondence: stanislaw.bielski@uwm.edu.pl

Abstract

Energy agriculture is one of the ways of producing clean energy. Crop production constitutes the basis for the sustainable profitability of agriculture, and agricultural products are traded on two markets: the food market and the energy market. This article reviews the literature on the conditions influencing biofuel production, with the aim of identifying the arguments supporting its expansion and the challenges associated with large-scale production. The study employs quantitative and qualitative desk research methods, the method of deduction, analysis and synthesis, the comparative method, and the expert method. Widespread application of biofuels requires a broader range of non-food raw materials (such as lignocellulosic biomass) and the advancement of conversion technologies used in bioethanol and biodiesel production. The main goal of ecofriendly energy generation should be to increase the energy output while minimizing environmental impacts. The findings from the literature review were collected, identified, and described as objectively as possible. The conclusions drawn are based on the authors' findings and expert opinions. The future of biofuels depends on the optimal choice of raw materials that ensure the highest production efficiency, low costs, and reduced emissions of harmful atmospheric pollutants. Thus, intensification of agricultural production of non-food crops (lignocellulosic biomass) for energy generation may lead to irreversible changes in the environment.

Keywords: biomass; biofuels; bioethanol; biodiesel; cellulosic ethanol; renewable feedstocks; energy security



Academic Editor: Diego Luna

Received: 8 October 2025

Revised: 9 November 2025

Accepted: 14 November 2025

Published: 20 November 2025

Citation: Marks-Bielska, R.; Bielski, S.; Kurowska, K.; Zielińska-Chmielewska, A. First-Generation Biofuels vs. Energy Security: An Overview of Biodiesel and Bioethanol. *Energies* **2025**, *18*, 6055. <https://doi.org/10.3390/en18226055>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Biomass is a renewable and locally produced energy source whose decentralized nature reduces the economy's vulnerability to fluctuations in energy supply. Furthermore, biomass is not affected by the future availability of conventional energy sources, making it a key component of a sustainable energy future. The use of biomass as a source of bioenergy will significantly reduce anthropogenic greenhouse gas (GHG) emissions. The carbon dioxide (CO₂) released during the combustion of plants is offset by the amount of CO₂ absorbed during their cultivation.

Biomass comprises all organic matter occurring in the biosphere. It includes organic matter of plant and animal origin, as well as the products resulting from the natural and

artificial transformation of organic matter [1]. Biomass is an increasingly popular renewable energy source with high growth potential due to its widespread availability around the world. Biomass can be a by-product of many agricultural and industrial processes. However, direct combustion of biomass is not always feasible in existing systems such as internal combustion engines. In many cases, biological or physicochemical treatment of biomass is required to ensure that the quality of the resulting biofuel is comparable to that of conventional fuels [2]. Extensive research efforts are currently focused on developing environmentally friendly and sustainable technologies for biofuel production. These efforts will contribute to supplementing conventional fossil fuels [3].

Biofuel can help reduce the global dependence on oil, thus stabilizing its high and volatile prices and enhancing social, economic and environmental sustainability [4]. For this reason, considerable emphasis has been placed on developing renewable energy sources that minimize our dependence on oil and reduce GHG emissions. Replacing oil and diesel with environmentally friendly fuels offers a promising solution for reducing human impact on the environment and dependence on oil.

Biofuels are generally classified as first- and second-generation types. First-generation biofuels are derived primarily from food-based crops such as maize, sugarcane, and oilseeds, whereas second-generation biofuels rely on non-food lignocellulosic feedstocks, including agricultural residues and dedicated energy crops such as miscanthus and switchgrass. This distinction is fundamental for evaluating biofuels' relative sustainability and impacts on food security [5,6].

In 2021, global biofuel production peaked at 175.9 billion L (124.9 L of bioethanol and 51.0 L of biodiesel), consuming 15.0% of maize grain, 1.2% of wheat grain, 1.7% of other fodder cereals, and 6.1% of vegetable oil [7].

Fossil fuels account for approximately 75% of global energy consumption for heat and electricity generation and around 20% for transport fuels [8]. Only a few countries possess significant fossil fuel reserves, which further deepens global energy dependence. The transport sector alone consumed about one-third of all crude oil in 2019 [9] and accounted for nearly 37% of global CO₂ emissions in 2020 [10]. Although fossil fuels continue to dominate global energy supply, their finite availability and adverse environmental effects highlight the need for alternative sources. Current estimates indicate that conventional oil reserves may satisfy rising demand for only the next four decades, while the transport sector remains the least reliant on renewables [11].

Climate change, energy security, and food security are among the key global challenges driving the search for sustainable biofuels, biochemicals, and bioenergy. Effective responses to these issues require coherent policy support, yet policy interventions in one area often create trade-offs in another. The concept of sustainable development emerged as a critique of the neoclassical model of optimization, emphasizing that long-term growth depends not on the accumulation of physical capital but on the preservation of natural capital [12]. Ensuring the non-deterioration of ecosystems has thus become a fundamental objective of modern economic development.

The environmental and social legitimacy of biofuels has long been the subject of debate. While biofuels are often promoted as a means of reducing GHG, numerous studies have questioned their net environmental benefits. Research highlights potential drawbacks such as biodiversity loss, land-use change, rising food prices, and increased competition for water resources [13]. In regions already affected by food insecurity, large-scale biofuel production may aggravate the problem rather than solve it.

Ensuring sustainable biomass production is therefore essential. Fertile soils should be used primarily for food production, whereas energy crops should preferably be grown on marginal or degraded lands. The development of sustainable biofuel systems requires

coordinated environmental policies, appropriate feedstocks and conversion technologies suited to local conditions, as well as efficient logistics for biomass transport to refineries.

Fischer et al. [14] emphasize that biofuels can play an important role in mitigating climate change by reducing net GHG compared to conventional fossil fuels. However, Hill et al. (2006) argue that the high energy inputs associated with fertilizer and pesticide production and feedstock processing may offset these benefits and, in some cases, lead to a net increase in GHG emissions [15]. Graham-Rowe [16] highlights that bioenergy development involves both synergies and trade-offs with other sustainability goals, such as biodiversity conservation, food security, and poverty alleviation. Similarly, other studies [17] note that assessments of biofuel sustainability often neglect key agronomic and regional factors that determine the real efficiency and environmental outcomes of biofuel systems.

The expansion of biofuels is primarily driven by rising energy demand, price volatility, and the need to diversify energy sources and improve energy security. Biofuels also support agricultural development by utilizing surplus crops and providing an additional source of income for farmers. In this context, the biofuel sector represents not only a technological innovation but also a form of social innovation aimed at enhancing rural development and promoting renewable energy transitions. Consequently, many governments have introduced active policy measures to stimulate biofuel production and integrate it into broader frameworks of sustainable energy and climate strategies [18].

The principal characteristics of sustainable alternative fuels include renewability and a lower environmental impact relative to conventional fossil fuels [19]. Various non-food raw materials, including algae and jatropha, are being studied to assess their suitability as alternative biofuel feedstocks. However, such plantations require considerable land resources [20]. Therefore, the optimal alternative raw materials for biodiesel production should be characterized by high availability and low cost.

This article reviews the literature on the conditions influencing the production of biofuels, including biodiesel and bioethanol, with the aim of identifying the arguments supporting its expansion and the challenges associated with large-scale production.

2. Results

2.1. Energy Security

A stable and continuous energy supply is essential for the proper functioning of every economy. Energy is a unique commodity as it has to be continuously supplied. The concept of energy security is strongly linked to economic factors, including employment, income growth, the development of energy markets, and socio-economic transformations in transport and information technology worldwide.

The definition of energy security varies depending on the context in which it is applied. Experts often note that energy security is difficult to define due to its multidimensional and multifaceted nature [21]. Definitional difficulties arise because countries are at different stages of economic development and experience various degrees of climate change and energy poverty. Each country must identify the specific challenges and threats to its energy security [22]. Therefore, the definition of energy security will be influenced by factors such as geographic location, international policy, technology development, environmental protection, financial markets, or even the probability of terrorist attacks. In countries that export energy, energy security is defined as the existence of reliable markets that ensure stable demand and income from the raw materials supplied. In turn, in countries that import energy, energy security implies a stable energy supply at optimal prices and a diversified supply structure. From the perspective of transit countries, energy security involves maintaining transmission networks and generating income from transit fees [23]. Based on a review of the literature, this article defines energy security as continuous and

uninterrupted access to energy at prices that are affordable to the state and consumers, as well as the rational and sustainable management of renewable and non-renewable energy resources.

Sustainable energy security implies that energy is available and affordable, and that different types and sources of energy are socially acceptable [24]. In Poland, since Russia's invasion of Ukraine in March 2022, increasing attention has been paid to the origin of energy supplies and to how the revenues from energy sales are used [25].

The economic impacts of the Russo-Ukrainian war have heightened global awareness of the risks associated with excessive dependence on Russian fossil fuels and of how such dependence reinforces authoritarian rule in Russia. The energy transformation has received considerable attention, but the measures taken so far proved to be insufficient. The dramatic reality of the war in Ukraine highlighted that energy transformation is an absolute necessity to safeguard the interests of economic groups, individual countries, enterprises, and households.

The so-called "Peak Oil" marked the point at which global oil production began to decline significantly. The above increased prices and caused many armed conflicts. In consequence, many national governments have become concerned about their ability to ensure energy security for their citizens. Most energy market experts agree that the era of cheap energy is irreversibly over [26].

Energy security requires an adequate supply of electricity at affordable prices and in a manner consistent with environmental protection laws. According to the European Union (EU), second-generation biofuels produced from lignocellulosic raw materials provide an effective means of reducing CO₂ emissions. Second-generation biofuels are produced from waste materials that are unsuitable for food production. Second-generation biofuels are also characterized by higher quality than first-generation biofuels and are more suitable for use in the automotive industry [27].

Energy security is a key concern in all countries. As a cornerstone of economic growth, energy security has attracted significant interest in both academic research and economic practice. The challenges and threats that have emerged since the beginning of the 21st century have underscored the growing importance of energy security.

The USA has transitioned from a net importer to a net exporter of natural gas, and energy consumption in Asia has increased due to demographic growth and the widespread use of electronic devices. Renewable energy sources, including food raw materials, also make an important contribution to energy security [22].

In environmental and socio-economic contexts, the development of bioenergy may have both positive or negative effects on the four pillars of food security: physical availability, economic access, utilization, and stability [28]. The rapid rise in global food prices in 2007–2008 was widely attributed to biofuels, triggering broad international debate [29].

Competition for agricultural resources between food and biofuel production has long raised concerns about rising food prices and global food security. Between 2006 and 2008, biofuels were identified as one of the contributing factors to the global food crisis. However, more recent analyses indicate that their influence on agricultural prices is smaller than initially assumed [30].

The allocation of arable land to energy crops can nonetheless reduce the potential for food production, indirectly affecting market stability. Meeting the food needs of a projected global population of nine billion by mid-century will require a 70–100% increase in agricultural productivity and significant changes in cropping structures [31].

The "food versus fuel" debate, addressed during the 2008 FAO High-Level Conference on World Food Security and the G8 Hokkaido Toyako Summit, remains a central issue in biofuel policy discussions. This competition can be analyzed at two levels: direct

competition for food and feed products, and indirect competition for agricultural land and resources [32].

Competition for agricultural resources involves not only land and water, but also the use of fertilizers, pesticides, agricultural machinery, labor, and capital. In this context, competition for farmland is the most serious problem, especially in the USA and Brazil. In the USA, the growing demand for bioethanol has increased the price of maize. Maize and soybeans are competitive crops, particularly in the American Midwest, and the acreage cropped with soybeans may decrease in this region. In Indonesia and Malaysia, the demand for biofuels has led to rapid deforestation, and 20% of biofuels in the UE are likely to be supplied by these two countries [28]. In Brazil, the area cropped with sugarcane has increased due to the growing demand for bioethanol. Sugarcane competes for land with other crops, including coffee beans, oranges, cotton, and rice. These processes induce changes in farmland use patterns, especially in the state of Sao Paulo which experienced direct changes in land use. Moreover, competition can also lead to indirect changes in land use in other areas. Competition for farmland can be direct or indirect [33]. Indirect changes in land-use patterns imply that natural ecosystems may be converted into crop plantations (for food or fodder production) to compensate for farmland lost to biofuel production.

Raw materials for the production of first-generation biofuels compete with agricultural commodities and agricultural production. First-generation bioethanol is obtained by fermenting plant biomass that is also suitable for food and feed production, including cereals (such as maize), sugarcane, and sugar beets. Ethanol is derived from the starches or sugars contained in these plants [34]. *Jatropha* is cultivated in other geographic regions, including Latin America, Asia, and Africa, and it competes with other feed crops. In addition to farmland, *jatropha* competes for resources such as water, machinery, fertilizers, pesticides, labor, and capital. Thus, the feedstocks for the production of lignocellulosic biofuels can compete with food crops, the demand for food, and agricultural production [31,33].

According to Altieri [35], large-scale bioenergy plantations in Latin America have undermined food security in this region, forcing people to resettle and marginalizing farmers. Overall, large soybean monocultures in Latin America have reduced employment in rural areas and led to greater income concentration.

Molasses is a by-product of sugar production. The use of molasses for bioethanol does not compete with food production. Surplus sugar beet and wheat yields do not compete with food or farmland, but they can compete in the animal feed market. Rice and wheat straw, which are second-generation biofuel feedstocks, can also pose competition in the feed market. Some biofuel feedstocks are also suitable for food production. For example, in Japan, potential competition between biofuel and food markets could negatively affect food security, but this impact is negligible given the country's low level of biofuel production [31].

Rising prices of food products affect lower-income consumers more severely than affluent individuals. Less wealthy consumers spend a considerable part of their total income on food, and staple foodstuffs constitute a large share of all food expenses in lower-income families, which are at greater risk of undernourishment than middle- and high-income households [31]. Competition between biofuels and food does not always have an adverse effect on food security. By increasing the prices of farm products, competition can create new income-generating opportunities for farmers and can promote the development of rural areas [36]. However, the use of agricultural raw materials for biofuel production inevitably competes with feed and food production [37].

The food-versus-fuel dilemma remains one of the key barriers to the sustainable expansion of biofuel markets. The issue is multifaceted, combining agricultural productivity

with land-use change and trade dynamics. Therefore, integrated policy tools that account for both food security and energy goals are needed to address these challenges.

Land conflicts arising from the food-versus-fuel dilemma can be mitigated by growing previously uncultivated crops or non-food crops on marginal land [38]. For example, research conducted in China demonstrated that fuel derived from biomass grown on degraded, infertile soils is not only as energy-efficient as maize-based ethanol but also has a neutral [39] or negative carbon balance, unlike ethanol produced from maize. Nevertheless, due to incentives to maximize efficiency, excess nitrogen may undermine carbon sequestration by increasing N₂O emissions [39].

2.2. Major First-Generation Biofuels

2.2.1. Biodiesel

Liquid and gaseous fuels, including bioethanol, biomethanol, biodiesel, dimethyl ether, bio-oil, biogas, and biomethane, are produced by subjecting biomass to biochemical, thermochemical, and biological conversion processes. Industrial-scale production of biofuels began in the 1980s with the introduction of transesterification. Most biofuels are produced by alcoholic fermentation of biomass rich in starch (ethanol), municipal waste, sewage sludge (biogas), as well as by dry distillation of wood (methanol) and transesterification of long-chain fatty acids (biodiesel). These fuels belong to the category of first-generation fuels, which are likely to dominate in the coming decades because they can be used in existing, unmodified engines, and are both economically viable and easy to produce. Other renewable feedstocks that are more difficult to process, such as cellulose, are also being explored for biofuel production and for the development of advanced biotechnological methods [19,40].

Alternative fuels produced from vegetable oils and animal fats, such as bioethanol and biodiesel, can partially or completely replace fossil fuels. Biodiesel is renewable, biodegradable, and less polluting than conventional diesel, as its combustion does not increase the net levels of CO₂ and GHG in the atmosphere [41,42]. In addition, biodiesel promotes the recycling of waste oils and has desirable properties, including higher lubricity, density, and cetane number, as well as low sulfur emissions and ignition temperature, which ensure reliable engine performance [43].

The growing interest in biodiesel has been driven by the demand for efficient compression-ignition engine fuels that offer both economic and environmental benefits [44]. Raw vegetable oils cannot be used directly as fuel due to their high viscosity and fatty acid composition. Their properties are improved by dilution with petroleum diesel, microemulsification with short-chain alcohols (methanol, ethanol, propanol, butanol) in the presence of an emulsifier, or by thermal and chemical conversion processes such as pyrolysis and transesterification. The latter, involving the exchange of glycerol with a low-molecular-weight alcohol in the presence of an acid or alkali catalyst, remains the most effective method of biodiesel production [44,45].

Biodiesel production has been controversial because it relies on methanol derived from fossil fuels. Research has shown that 35% of the total primary energy requirement for biodiesel production comes from fossil fuels [46]. Methanol accounts for about 10% of the feedstock, indicating that biodiesel is not completely renewable [47].

A key sustainability concern in biodiesel production is the dependence on fossil-derived methanol as the alcohol reagent in transesterification. While typical industrial processes do not disclose exact percentages, methanol inputs can represent a non-negligible fraction of total material input. Emerging production routes such as CO₂ hydrogenation and biogas reforming to generate renewable methanol are under development and may enable a more fully renewably sourced biodiesel value chain [48,49].

The large-scale use of biodiesel entails high costs, with raw materials—mainly vegetable oils—accounting for more than 80% of total production costs [50–53]. Furthermore, the vegetable oils employed in biodiesel production are also used in the food industry, creating direct competition between these sectors. Used cooking oil (UCO) is a cheaper alternative feedstock for biodiesel production [54,55]. The large-scale use of biodiesel is hindered by difficulties in obtaining homogeneous feedstocks that ensure consistent fuel quality [56]. The data summarized in Table 1 highlight both the progress and the methodological inconsistencies in the assessment of first-generation biofuels. Although recent studies incorporate broader sustainability metrics, variations in system boundaries, data quality, and regional assumptions continue to limit cross-study comparability and policy relevance.

Table 1. Review of selected studies on first-generation biofuels.

Authors	Region/Scope	Feedstock/Focus	Methodology/Type of Study	Main Findings/Notes	Limitations
Hill et al. (2006) [15]	USA/global	Corn ethanol, biodiesel	Comparative environmental/economic analysis	Low net GHG benefits for some feedstocks due to upstream inputs; raised food–fuel concerns.	Focuses on early-generation technologies; limited life-cycle data and outdated agricultural practices.
Graham-Rowe (2011) [16]	Global	Mixed	Policy review	Highlights food security risks	Limited data integration
Hall et al. (2009, 2014) [57,58]	Global	Various biofuels	Conceptual EROI framework	Identifies minimum EROI threshold	Theoretical framework; not based on empirical production data
Gomiero (2015) [59]	Global	Palm oil	Socio-economic assessment	Describes “energy colonialism”	Limited quantitative data; lacks updated LCA comparisons
Murphy et al. (2022) [60]	Global	Major energy carriers, incl. biofuels	EROI review & harmonization	Harmonizes EROI estimates across fuels	Limited coverage of new conversion technologies
Arshad et al. (2022) [61]	Global	Camelina (bio-based uses)	Review on camelina valorization	Camelina as a promising non-traditional oilseed for bio-based products and fuels	Limited LCA or EROI evaluation
Bouter et al. (2024) [62]	Global	Biofuels (various)	Meta-analysis of LCA studies	Quantified mean carbon footprint for ethanol and biodiesel; regional emission variability	Meta-analysis limited by inconsistent functional units and reporting standards
Papagianni et al. (2024) [63]	Global	Ethanol, biodiesel	Review and meta-analysis of EROI studies	Identifies methodological causes of EROI variation (feedstock, system boundary)	Lacks differentiation between first- and second-generation biofuels
Malik (2024) [64]	Global	Sustainable alternatives and policy context	Narrative review	Synthesizes policy drivers, market dynamics and sustainability constraints	Lacks quantitative modeling or case analysis
Kardan et al. (2024) [65]	Global	Renewable methanol	Review on CO ₂ hydrogenation to methanol	Advances in routes for renewable methanol (relevance to biodiesel feedstock inputs)	Focuses on process engineering; not integrated with biofuel life-cycle impacts

In summary, biodiesel and bioethanol production from first-generation feedstocks remains constrained by competition with food resources and dependency on fossil-based methanol inputs. Integrating life-cycle and economic assessments could improve sustainability evaluation.

2.2.2. Bioethanol

Bioethanol, namely alcohol derived from biomass, is the most popular biofuel in the global transport sector [66]. Alcohol fermentation is the oldest and best-known biotechnological process for obtaining bioethanol. Bioethanol is derived from biomass rich in sugar and starch, and it has been produced as an energy source since the early 20th century, with industrial-scale production beginning in the 1970s. Bioethanol derived from sugar/starch is classified as first-generation bioethanol [67]. Since its introduction, this biofuel has been produced from crops containing starch (cereal grains, maize, potato tubers) or sucrose (sugarcane, sugar beets). Sugarcane is a grass plant that typically grows in tropical and subtropical climates. Unlike the biofuel derived from starchy biomass, the production of bioethanol from sucrose-rich crops does not require a saccharification stage because sugars are already easily available, which simplifies the process [68]. Two-thirds of the world's sugar production comes from sugarcane, and a third originates from sugar beets [69]. In some countries, including China, bioethanol is produced from crops such as cassava, sweet potatoes, and sorghum rather than cereal grains. However, the use of non-cereal crops for bioethanol production can also pose a threat to food security. Cassava and sweet potatoes are not staple foods, but they are important components of the human diet, especially for lower-income consumers. The use of sorghum in biofuel production is also problematic. Although this crop is grown on marginal land, sorghum cultivation increases the demand for water and fertilizers, thus reducing their availability for food production and potentially undermining food security [70].

Compared to traditional fuels, ethanol and higher alcohols have many advantages over petroleum derivatives, including higher combustion energy and lower toxicity. In addition, alcohols have a higher octane number than fossil fuels. New technologies make it possible to convert cellulosic biomass into ethanol, and they have attracted interest from researchers [71]. A steady supply of low-cost raw materials is essential to maintain price competitiveness and enhance production efficiency. Lignocellulosic biomass is considered the most promising feedstock for bioethanol production due to its availability, low cost, as well as the fact that, unlike sugar- and starch-containing biomass, it does not compete with food production. Based on the definition of first-generation bioethanol, bioethanol produced from lignocellulose is referred to as second-generation bioethanol or cellulosic ethanol [72]. However, cellulosic biomass is more difficult to convert to ethanol than feedstocks rich in sugar or starch [73].

Farrell et al. [13], Tilman et al. [74], and Sims et al. [75] argue that ethanol produced from low-input cellulosic biomass grown on grasslands or marginal land, or derived from waste biomass, can provide substantially greater energy yields and environmental benefits than biofuels derived from food crops. However, the use of harvest residues and agricultural 'waste' for biofuel production has stirred controversy. Some authors maintain [76] that there is no 'waste' in agricultural ecosystems. Agricultural by-products and harvest residues play a very important role as sources of organic matter and other substances that improve soil fertility. Fields deprived of harvest residues are more prone to soil erosion, which adversely affects agricultural productivity. In the USA, the removal of maize residues not only led to a substantial decline in maize yields and soil quality [77], but also contributed to an overall increase in GHG emissions.

More recent life-cycle assessments and agronomic studies emphasize that excessive removal of agricultural residues can deplete soil organic carbon (SOC) and depress microbial activity, thereby undermining soil fertility over time [78]. For example, a study conducted by Blanco-Canqui [79] in the USA as well as recent research [80] demonstrated that extensive residue removal impairs soil structure and reduces long-term productivity.

For these reasons, second-generation lignocellulosic biomass constitutes alternative feedstock for bioethanol production. Lignocellulosic biomass is inexpensive, widely available, and does not compete with food and/or feed production, making it the most promising feedstock [81]. Although the price of cellulose has decreased more than tenfold since the 1990s, it still accounts for 20% of the cost of producing bioethanol from lignocellulosic feedstocks [82]. Agricultural by-products (maize stover, wheat and rice straw), sugarcane pulp, wood (hardwoods and conifers), grass, municipal waste and dedicated energy crops (miscanthus and switchgrass) are the most popular sources of lignocellulose [83]. Maize stover has many advantages over other energy crops. It is widely available, cheap, does not compete with food production, and does not require the expansion of cultivated areas [84].

Unlike starch-based feedstocks for bioethanol production, cellulosic biomass is derived from non-food crops. Ethanol prices are influenced mainly by the prices of corn grain and gasoline. Over the past ten years, ethanol prices have fluctuated relative to gasoline and grain. Gasoline prices rose when corn grain was relatively cheap, and ethanol trade was linked to gasoline prices. However, as more corn grain was used in ethanol production, the price of ethanol fluctuated in relation to crude oil prices. The correlation between the price of corn grain and the price of ethanol is expected to weaken when large quantities of ethanol are produced from cellulosic biomass [85].

Energy crops, particularly grasses (switchgrass and miscanthus), show great potential as feedstocks for second-generation biofuel production [86]. Switchgrass is more drought-tolerant and can adapt to different soil types and climates. In turn, miscanthus is a high-yielding energy crop. Both switchgrass and miscanthus are perennial grasses with C4-type photosynthesis and a high carbon fixation rate. These factors accelerate the rate of photosynthesis and contribute to rapid plant growth [87]. These grasses can be cultivated on marginal land and require little water. Together with agricultural by-products, grasses can be used as feedstocks for biofuel production, although they cannot be grown in all geographical regions. For example, low winter temperatures and short growing seasons are the main factors limiting the growth of C4 grasses in northern Europe [88]. Pests and pathogens pose a considerable challenge to the cultivation and sustainability of energy crops [89]. However, the most serious problem that needs to be addressed is the high cost of bioethanol production. Larger quantities of diverse types of lignocellulosic biomass could be processed in biorefineries, which would reduce bioethanol production costs and make bioethanol more economically competitive than fossil fuels [90].

In summary, the data on biofuel production showed that between 2010 and 2024, a systematic increase in global biofuel production was observed, despite periodic declines in some regions (Table 2). The total output of all biofuel types exceeded 167 billion liters in 2024, representing an increase of approximately 45% compared with 2010. North America (primarily the United States) has remained the world's largest producer of bioethanol. South America—especially Brazil—also recorded dynamic growth, expanding production from 26.2 to 36 billion liters. In contrast, the European Union experienced a stable but slower increase, likely constrained by limited availability of arable land for feedstock cultivation and the implementation of sustainability-oriented policies. Production in China was more volatile, with a sharp decline in 2015 followed by a renewed upward trend toward 2024.

In 2010, the EU was the leading producer of biodiesel. By 2024, biodiesel output in the EU had grown by roughly 30%, while both American continents and China tripled their production during the same period.

Table 2. Biofuel production in selected regions (million liters).

Region	2010	2015	2020	2024
bioethanol				
European Union	5300	5250	5000	6200
South America	26,200	27,260	32,500	36,000
North America	52,000	56,000	52,800	61,400
China	3150	720	5000	4540
World	86,000	116,000	105,000	118,200
biodiesel (FAME—Fatty Acid Methyl Esters)				
European Union	9000	11,000	11,500	12,000
South America	3500	5000	8000	9000
North America	2500	3500	8500	9500
China	1000	1500	2000	2700
World	13,000	31,000	39,000	41,000
biodiesel (HVO—Hydrotreated Vegetable Oil)				
European Union	100	300	1500	2500
South America	50	100	300	400
North America	200	800	3000	5000
China	0	50	200	300
World	400	1500	5200	8200

Source: [91–95].

Hydrotreated vegetable oil (HVO) emerged as the fastest-growing segment of the biofuel market, increasing from 0.4 to 8.2 billion liters. North America became the clear global leader, accounting for approximately 60% of global HVO production in 2024.

Bioethanol continues to dominate the global biofuel market, representing about 70% of total biofuel output in 2024. While FAME biodiesel remains important, its relative share is declining in favor of HVO, which is gaining market share due to its superior combustion properties and better compatibility with modern diesel engines. China entered the biofuel market later than other major regions; however, its rapid growth trajectory suggests that it will play an increasingly important role in the coming years.

Overall, global trends indicate a diversification of biofuel sources and further development of HVO technologies as well as second-generation biofuels, aligning with long-term climate neutrality objectives for 2050.

2.3. Advantages and Disadvantages of First-Generation Biofuels

2.3.1. Environmental Effects

Biofuels have many technical and environmental advantages over conventional fossil fuels, making them an attractive alternative solution in the transport sector [96]. Direct benefits include reduced GHG emissions (mainly CO₂ and methane), diversification in the fuel sector, biodegradability, improved vehicle efficiency, and development of the agricultural produce market [97]. However, the conversion of energy crops to biofuels requires fossil energy inputs. The well-to-wheels analysis revealed that first-generation biofuels reduce GHG emissions by 20–70% compared with petroleum-based fuels [14].

The widespread production and consumption of biofuels bring a range of economic benefits, including the promotion of sustainable development and fuel diversity, the creation of new rural jobs, increased tax revenues, greater investment in fixed assets in agriculture, and enhanced international competitiveness [98]. Proponents of production argue that energy crops foster rural development by diverting more land to biomass production and improving employment opportunities in the countryside [97]. Bioenergy derived from agricultural crops can help diversify and increase farm incomes. It can also contribute to im-

proved energy security, although biofuels derived from agricultural crops can pose a threat to food security. Therefore, second-generation liquid biofuels, produced from non-food raw materials such as cellulosic and lignocellulosic biomass, should be introduced as soon as possible. However, the impact of renewable energy (including biomass) on the environment and energy availability should not be overestimated. Sustainable energy management is an important driver of local development. It is particularly crucial in agricultural regions, where biomass resources are constantly renewable [99].

The impacts and effectiveness of bioenergy are difficult to assess. Most contemporary studies on energy assessment analyze this issue within a relatively narrow scope. The Life Cycle Assessment (LCA) is one of the most reliable and widely used tools, but it does not capture and reflect the complexity of all processes [100]. Despite the above, LCA remains a key research instrument that encompasses all stages of a product's life cycle. In the literature, the LCA approach has been applied to assess the environmental impacts of agricultural crops and food products [101].

Numerous studies have analyzed the energy efficiency and GHG emission profile of biofuels. Yet, the reported results are highly discrepant. Some researchers have concluded that biofuels represent an effective alternative to petroleum, whereas others argue that biofuels and biomass are less efficient than fossil fuels. The reasons why highly esteemed scientists have arrived at such contradictory conclusions warrant further investigation. The following subsections discuss the environmental, economic, and social dimensions of biofuel production to ensure coherent assessment.

According to Ridley et al. [102], more interdisciplinary research is needed to assess the complex trade-offs and feedback relationships associated with an energy strategy capable of generating far-reaching consequences. Biofuels are evaluated using models that tend to consider various issues separately, such as the negative effect of biofuel production on food security, poverty, and GHG emissions resulting from land-use change. As a result, considerable discrepancies exist among assessments of biofuels' effects [102].

The lack of an integrated approach not only hinders the analysis of the quality of the applied models but can also lead to errors in data interpretation. Searchinger et al. have recently identified serious flaws in the three key models used to formulate government policies in the USA and Europe [103]. They concluded that the reduction in GHG emissions attributed to biofuels was, in fact, achieved through decreased food production. The tested models do not account for the fact that some crops diverted from food to biofuel production are not replaced by plants cultivated in other locations.

Pimentel and Patzek [96] and Tilman et al. [74] identified the threats associated with biofuels, particularly first-generation biodiesel and bioethanol, and presented well-reasoned arguments to support their claims. International research on the sustainable production of biofuels from agricultural crops has produced contradictory findings [31]. However, none of the reviewed studies analyzed the competition between biofuel and food, or the relationship between biofuel and food security.

Several large-scale studies of rural ecosystems [103–105] have emphasized that current industrial agricultural management systems, which favor crop production in monocultures, have adverse effects on rural ecosystems, including multi-crop biofuel monocultures [35]. The negative impacts of extensive grain monocultures on the environment and human health have been well documented. For example, the demand for herbicides, including atrazine, tends to be higher in large maize monocultures. These compounds have been shown to cause endocrine disorders, especially in vertebrates. Furthermore, maize monocultures have a high demand for nitrogen fertilizers, which leads to elevated nitrate levels in water [105]. High levels of nitrogen fertilization also cause physiological imbalance in plants, which contributes to pest infestations and disease epidemics that reduce yields.

2.3.2. Economic Aspects

Raw material prices significantly influence bioethanol production costs and, depending on the type of feedstock, can account for up to 40–75% of total costs [106]. According to other authors, raw materials account for 70–80% [107] up to 90% [108] of the total production costs of biofuels from cereal grains. Biofuel production is often economically unviable without financial support from the government. Biofuels, in particular biodiesel, are often more expensive than fossil fuels [109]. Bielski [18] also concluded that the profitability of rapeseed methyl ester (RME) production in Poland is often questionable. Financial support, price intervention, and trade barriers play a key role in the development of biofuels [110]. With the government's support, biofuels can become less costly than fossil fuels. For instance, in Thailand, the E85 fuel blend was 30–40% cheaper than premium petrol in 2008, whereas the Indonesian government planned to subsidize biofuels if their prices exceeded those of fossil fuels [111]. The competitive advantage of biofuels also depends on the region of production. Owing to their specific characteristics, agricultural regions producing biofuels can be more competitive than others.

The energy value of biofuels, particularly their energy return on energy invested (EROI), has long been the subject of debate. The EROI values of biofuels are typically very low. These values vary significantly across studies; EROI values below 1 have been reported for processed maize grain (0.75 [96], 0.80 [112], and 0.92 [113]) and for other oilseeds such as white mustard, spring rape, and camelina (0.5–0.8) [114]. However, in some studies, this parameter exceeded 1, reaching 1.1 [114], 1.20 [13], 1.25 [14], 1.21–1.35 [115], 1.20–1.70 [57], and even 5.40–5.90 or 6.85 [116], depending on the intensity of production [117]. According to Hall et al. [58], much higher EROI values (8–10) are noted only for sugarcane produced in Brazil. In contrast, fossil fuels have an EROI of 20–30 or more [57,99]. The fact that some biofuels have higher EROI values does not alter the general perception that biomass has a low energy efficiency [57]. Recent market data [8] indicate that the global average cost of biodiesel production is 20–30% higher than that of petroleum diesel, depending on regional feedstock prices. However, policy mechanisms such as carbon credits and renewable fuel mandates have narrowed this gap in several EU countries. A summary of EROI indicators for various raw materials is presented in Table 3.

Table 3. Reported EROI values for selected first-generation biofuels and fossil fuels.

Feedstock/Fuel	Region	Reported EROI Range	Source(s)
Maize ethanol	USA, EU	0.75–1.1	[63,96,112,113]
Sugarcane ethanol	Brazil	8–10	[57,117]
Rapeseed biodiesel	EU	1.1–1.7	[57,60,114]
Soybean biodiesel	USA, South America	1.2–2.5	[63,117]
Camelina biodiesel	Europe	0.5–0.8	[64,114]
White mustard biodiesel	Europe	0.5–0.8	[114]
Palm-oil biodiesel	Southeast Asia	2.8–4.5	[62,117]
Maize stover ethanol (residues)	USA	2.0–3.5	[117]
Petroleum diesel	Global	20–30	[57,117]
Petroleum gasoline	Global	25–30+	[57,117]

Feedstocks used for biofuel production have low energy density, which represents a major limitation [13,15,96]. Large quantities of biomass must be processed to obtain the required energy output, which is both time- and capital-consuming. For this reason, some countries, including Poland, have implemented administrative and fiscal regulations on the biofuel market to promote biofuels, achieve social objectives such as environmental protection and improved energy security, and support rural development by increasing the demand for agricultural products [18].

2.3.3. Social and Policy Dimensions

Since 2005, the global agricultural market has been destabilized by the development of the biofuel market. The production of biofuels from agricultural raw materials has been increasing steadily ever since. In market economies, the economic potential of agricultural crops for biofuel production is determined by the ratio between raw-material and crude-oil prices, as well as by the conversion factors for different types of feedstocks. Biofuels are not economically viable when this ratio is too high. Governments have actively promoted biofuel production to enhance energy security, mitigate climate change, and support the agricultural sector. Government subsidies, mandates, and other policies have created a market for biofuels and increased industrial demand for feedstock crops. As a consequence, many decisions to convert agricultural crops into fuel were driven by government incentives rather than by economic rationale [118].

Most biofuel policy instruments involve consumption subsidies (such as direct subsidies or tax breaks), import tariffs, and mandatory limits specifying the minimum and maximum shares of organic components in liquid fuels. Although the policies implemented in different countries and regions may vary in the configuration and scope of the instruments applied, they all create artificial demand for agricultural products. The above has led to a decline in the availability of raw materials on the global market [119].

Biofuel policy regulations stimulate demand but limit its flexibility, for example by prescribing minimum admixture shares in fuels. The demand for biofuels is quite inelastic as it cannot fall below the mandatory minimum shares or rise above the limits imposed by the combustion engine technology. As a result, prices may rise significantly and fluctuate considerably under shock conditions such as drought, flooding, or overproduction [120]. The prices of agricultural products are driven mainly by increased demand for biofuels [121].

High crude oil prices also stimulate the interest in alternative sources of energy. Between 2014 and the Russian invasion of Ukraine in 2022, the relationship between oil prices and agricultural prices has weakened—oil prices declined, the profitability of biofuel production decreased, and the EU announced plans to lower the mandatory minimum share of biofuels in transport fuels. These relationships have strengthened over time, although their nature remains unclear. Granger causality tests have shown that oil prices affect the prices of maize, wheat, soybeans, and sugarcane [1,11]. This effect carries over to the prices of bioethanol and biodiesel [122]. The relationship between the prices of agricultural products and oil can be considered not only in terms of price levels, but also in terms of the transmission of volatility between prices. In this context, Serra et al. [123] argued that greater volatility in the oil market after 2005 was accompanied by greater volatility in agricultural product prices.

The development of the biofuel market affects not only the prices of raw materials [29] but also those of other crops with minimal use in biofuel production, such as wheat and rice. This is due to the limited supply of land and substitution relationships, i.e., potential changes in the prices of other crops. Moreover, rising prices of cereals and oilseeds drive up feed costs and, consequently, the prices of animal products [122].

In developing countries, large corporations and governments have long exerted pressure on farmers to convert land for the cultivation of energy crops. Land-use changes have contributed to social conflicts in countries such as Indonesia, Malaysia, Columbia, Brazil, and Tanzania. According to reports, small farmers and local residents have been evicted from their land, workers on large plantations have faced abuse, and food security among the poorest populations has declined [124,125]. Energy companies such as BP, Shell, Total (Total Energies), D1 Oils, and Sun Biofuels recognized that biofuel feedstocks could be sourced cheaply from Africa and estimated that 30–50% of the continent's territory was suitable for energy crop cultivation [126]. Gomiero [59] argued that developed countries

of the Global North are engaging in a new form of ‘energy colonialism’, exploiting the agricultural ecosystems and cheap labor of the Global South to produce low-cost bioenergy for their transport sectors.

The alleged environmental benefits of biofuels, particularly their potential to reduce GHG emissions and limit the depletion of fossil fuels, are the main arguments in favor of renewable energy policies. However, a more detailed analysis indicates that the problem is far more complex. The apparent environmental benefits of biofuels appear to be more limited than previously assumed. There is evidence to indicate that in some cases, biofuels may exacerbate the existing problems. Feedstocks for first-generation biofuels require agricultural practices that are as intensive as those applied in the production of other crops, which has a detrimental impact on soil and groundwater and causes more pollution. The use of harvest residues is also questionable as it entails increased consumption of agricultural inputs. Therefore, the EU’s energy policy, aimed at reducing GHG emissions in its Member States, may in fact lead to a net increase in emissions [59].

For biofuels to replace a small proportion of the fossil fuels that are currently consumed, more extensive and intensive agricultural practices would need to be introduced, with strong impacts on soil, water resources, and biodiversity. In turn, the widespread use of agricultural chemicals causes various types of pollution, and biofuels are likely to exacerbate these problems [104,127]. Therefore, some researchers have called for the adoption of more sustainable and agroecological farming practices to preserve ecosystem services related to biodiversity, mitigate agriculture’s impact on natural resources, reduce pollution, and avert a global biodiversity crisis [128]. Extensive cultivation of crops suitable for biofuel production would reinforce two major drivers of global biodiversity loss: the conversion of natural areas into monocultures and the spread of invasive species [129].

To mitigate these impacts, recent research promotes agroecological practices such as intercropping, crop rotation, and the use of cover crops, which can enhance biodiversity while maintaining bioenergy yields [130,131].

Biomass combustion is considered carbon-neutral by some researchers. This claim relies on rather simplified reasoning by assuming that CO₂ released during combustion is completely assimilated by plants, thus yielding zero net emissions. However, there is considerable evidence to suggest that this is not the case. In tropical ecosystems, the conversion to energy crop cultivation leads to a loss of aerial biomass. Energy crops are also responsible for the release of substantial amounts of soil carbon; in tropical forests, approximately 50% of total carbon is stored in the soil. Energy crop plantations will never store as much carbon as native ecosystems, which leads to net carbon emissions. Conversion of grasslands to energy crop plantations will result in a net release of carbon stored in native ecosystems. Even if energy crops are assumed to generate zero emissions, the carbon previously stored in the ecosystem will continue to be lost and released to the atmosphere [104,132]. Other authors have also emphasized that the production of biofuels can generate net carbon emissions, particularly if tropical forests and previously uncultivated land are converted to energy crop plantations [104,133].

First-generation biofuels rely on intensive agriculture. Subsidies can exacerbate the existing problems by encouraging monocropping—such as maize in the USA—which could pose a serious threat to agricultural ecosystems. Second-generation biofuels may alleviate the conflict with food production, but converting large amounts of harvest residues and agricultural waste into energy may be inefficient and could compromise the long-term fertility and biological diversity of soil. Some of the most promising alternative non-food crops introduced in certain countries are invasive species that can cause severe environmental damage in the future. It has long been maintained that biofuels can play an important role in reducing GHG emissions. However, this assumption has been questioned already

several decades ago. Recent analyses suggest that, when all factors are properly accounted for, biofuels may not help reduce GHG emissions. On the contrary, extensive production of energy crops can increase emissions, exacerbate global warming, and contribute to deforestation of tropical ecosystems.

Biofuels cannot compete with fossil fuels in the energy market. Their production is profitable only if subsidized with public funds and supported by legal mandates requiring the blending of petrol with biofuels. Fossil fuels are also subsidized, but to a much lesser extent. It should also be noted that agricultural externalities such as water depletion, loss of soil fertility, environmental pollution, and carbon emissions are not taken into account. The growing trade in biofuels may adversely affect ecosystems and food production in biofuel-producing countries, particularly in developing economies. A broader, deeper, and longer-term analysis is needed. Land expropriation and other social and economic problems should be monitored. Subsidies should not be granted if they can exacerbate social and environmental problems. Instead, they should be used to support farmers in both developing and developed countries, and to adopt energy-efficient and environmentally friendly agricultural practices that can reduce GHG emissions, prevent soil erosion, decrease water consumption, free the environment from toxic pollutants, and protect biodiversity.

In Northern and Central Europe, including Poland, rapeseed is the dominant oilseed crop, and rapeseed oil is used mainly for biodiesel production. The share of vegetable oils in biodiesel production has increased significantly. The share of global vegetable oil production used for biodiesel increased nearly six-fold, from 2.6% in 2005 to 15.4% in 2021, and EU countries saw an increase from 27.3% to 71.2% [134]. Among biodiesel feedstocks, oil palm plantations have the highest yields per hectare. In turn, biodiesel production costs can be reduced by using waste products from the fat and oil industry and recycled cooking oils [135]. According to some researchers, recycled cooking oil is an effective substitute for vegetable oils in biodiesel production, as it reduces production costs and provides a solution for managing used oil [136]. Emerging non-food energy crops, such as *Camelina sativa* and *Ricinus communis*, offer promising alternatives. In particular, castor is gaining attention as a high-oil crop adaptable to semi-arid and Mediterranean regions [137], and camelina has been shown to perform well under Mediterranean conditions as a flexible oilseed crop [138]. Biodiesel production from UCO is one of the most efficient and economic methods of recycling this waste product [139]. Bobadilla et al. [140] demonstrated that biodiesel produced from waste cooking oil was of high quality and that its fuel parameters met international standards.

The interactions among the environmental, economic, and social factors discussed above highlight the multifaceted nature of biofuel development. A comprehensive synthesis of these aspects, supported by insights from recent studies, is presented in the following subsection.

2.4. Synthesis and Critical Insights

The review of first-generation biofuels reveals a complex and often contradictory body of evidence. While biodiesel and bioethanol have contributed to partial energy diversification and reduced dependence on imported fossil fuels [17,18,56], their overall sustainability remains under debate. The environmental benefits of biofuels, including lower net GHG emissions compared to conventional fuels [14,15], are often offset by indirect land-use change, biodiversity loss, and agricultural intensification [16,77]. These impacts vary considerably by region and production system, highlighting the need for context-specific evaluation rather than generalized conclusions [19].

From an economic perspective, biofuels have supported rural incomes and enhanced energy security by promoting the use of domestic feedstocks [22,84]. However, their

profitability remains highly sensitive to fluctuations in oil prices, government subsidies, and feedstock availability [23,89]. The relatively low EROI of several first-generation biofuels—estimated between 1.0 and 1.7 for maize- and rapeseed-based fuels [15,100]—limits their long-term competitiveness unless process efficiencies are improved or renewable methanol and waste-derived inputs are introduced [101].

The social and policy dimensions of biofuel expansion present both opportunities and challenges. On the one hand, biofuel programs can stimulate rural development, generate employment, and foster innovation [18,106]. On the other hand, when arable land and water are diverted from food production, such initiatives may exacerbate social inequalities and threaten food security [13,16,87]. These findings underscore the necessity for coherent governance frameworks that balance biofuel expansion with climate, biodiversity, and food policy objectives [12,86].

Synthesizing the reviewed literature reveals three critical research gaps. First, quantitative models linking biofuel production intensity with national energy dependence remain scarce and fragmented [56]. Second, existing sustainability assessments rarely integrate environmental, economic, and social indicators into a unified analytical framework [22,99]. Third, few studies comprehensively address dynamic trade-offs among land use, food availability, and renewable energy expansion [16,83].

Future research should therefore aim to develop integrated assessment tools combining LCA, EROI, and socio-economic indicators. Such models would enable policymakers to quantify trade-offs and guide the transition toward sustainable bioenergy systems that genuinely contribute to long-term energy resilience and environmental protection.

3. Conclusions

Threats to energy security are driving investment in new technologies, particularly renewable energy sources, including biomass conversion and distributed energy generation systems. Recent trends indicate that renewable energy generation will be the most rapidly growing sector with development potential in rural areas. At present, the agricultural sector provides not only food but also biomass for energy production. Due to their decentralized nature and reliance on local resources, renewable feedstocks can, to a certain extent, enhance energy security and help reduce energy prices. Governments are increasingly promoting the production of liquid biofuels for transport as a means to address major challenges such as fossil fuel price volatility, GHG emissions, and the socio-economic development of rural areas. The biofuel production targets adopted by different countries, and their social and environmental impacts, warrant further research into sustainability of various biofuels. Biofuels may offer numerous advantages, promoting the social and economic development of rural areas through job creation and the establishment of bioenergy production facilities.

The results of this review indicate that while first-generation biofuels contribute to energy diversification, they cannot ensure long-term sustainability due to environmental and food competition. Future research should focus on integrating life-cycle, socio-economic, and policy frameworks to optimize feedstock use and improve energy security without compromising food availability. Developing cost-efficient second-generation technologies remains the most promising direction.

Author Contributions: Conceptualization, S.B. and R.M.-B.; literature review, S.B., R.M.-B., K.K. and A.Z.-C.; formal analysis, S.B., R.M.-B., K.K. and A.Z.-C.; writing—original draft preparation, S.B., R.M.-B. and K.K.; writing—review and editing, S.B., R.M.-B., K.K. and A.Z.-C.; supervision, S.B. and R.M.-B.; project administration, S.B. and R.M.-B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Mehedintu, A.; Sterpu, M.; Soava, G. Estimation and forecasts for the share of renewable energy consumption in final energy consumption by 2020 in the European Union. *Sustainability* **2018**, *10*, 1515. [CrossRef]
2. Soltero, V.M.; Chacartegui, R.; Ortiz, C.; Velázquez, R. Potential of biomass district heating systems in rural areas. *Energy* **2018**, *156*, 132–143. [CrossRef]
3. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy From Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. Available online: <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF> (accessed on 13 November 2025).
4. Chavez, E.; Liu, D.H.; Zhao, X.B. Biofuels production development and prospects in China. *J. Biobased Mater. Bioenergy* **2010**, *4*, 221–242. [CrossRef]
5. Yıldızbaşı, Z. Biofuels, E-Fuels, and Waste-Derived Fuels: Advances, Challenges, and Future Directions. *Sustainability* **2025**, *17*, 6145. [CrossRef]
6. Visković, J.; Dunderski, D.; Adamović, B.; Jaćimović, G.; Latković, D.; Vojnović, Đ. Toward an Environmentally Friendly Future: An Overview of Biofuels from Corn and Potential Alternatives in Hemp and Cucurbits. *Agronomy* **2024**, *14*, 1195. [CrossRef]
7. REN21. Renewables 2022 Global Status Report. Available online: https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Full_Report.pdf (accessed on 9 September 2025).
8. International Energy Agency (IEA). Energy Statistics Data Browser. 2024. Available online: <https://www.iea.org/data-and-statistics> (accessed on 9 September 2025).
9. International Energy Agency (IEA). World Energy Outlook 2021. Available online: <https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf> (accessed on 9 September 2025).
10. Nunez, C. Fossil Fuels, Explained. 2019. Available online: <https://www.nationalgeographic.com/environment/energy/reference/fossil-fuels/> (accessed on 9 September 2025).
11. Zhang, Y. The links between the price of oil and the value of us dollar. *Int. J. Energy Econ. Policy* **2013**, *3*, 341–351.
12. Zielińska-Chmielewska, A.; Olszańska, A.; Kaźmierczyk, J.; Andrianova, E.V. Advantages and Constraints of Eco-Efficiency Measures: The Case of the Polish Food Industry. *Agronomy* **2021**, *11*, 299. [CrossRef]
13. Farrell, A.E.; Plevin, R.J.; Turner, B.T.; Jones, A.D.; O'Hare, M.; Kammen, D.M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311*, 506–508. [CrossRef] [PubMed]
14. Fischer, G.; Prieler, S.; van Velthuisen, H.; Lensink, S.M.; Londo, M.; de Wit, M. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. *Biomass Bioenergy* **2010**, *34*, 159–172. [CrossRef]
15. Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. USA* **2006**, *103*, 11206–11210. [CrossRef]
16. Graham-Rowe, D. Agriculture: Beyond food versus fuel. *Nature* **2011**, *474*, S6–S8. [CrossRef]
17. Arodudu, O.T.; Helming, K.; Wiggering, H.; Voinov, A. Towards a more holistic sustainability assessment framework for agro-bioenergy systems—A review. *Environ. Impact Assess. Rev.* **2017**, *62*, 61–75. [CrossRef]
18. Bielski, S. Economic and legal aspects of biofuel production for own use. *Acta Sci. Pol. Oeconomia* **2012**, *11*, 5–15. Available online: <https://aspe.sggw.edu.pl/article/view/556> (accessed on 3 October 2025).
19. Nigam, P.S.; Singh, A. Production of liquid biofuels from renewable resources. *Prog. Energy Combust. Sci.* **2011**, *37*, 52–68. [CrossRef]
20. Dorado, M.P. Raw materials to produce low-cost biodiesel. In *Biofuels Refining and Performance*; Nag, A., Ed.; McGraw-Hill: New York, NY, USA, 2008; pp. 107–147.
21. Marks-Bielska, R.; Bielski, S.; Pik, K.; Kurowska, K. The importance of renewable energy sources in Poland's energy mix. *Energies* **2020**, *13*, 4624. [CrossRef]
22. Cherp, A.; Jewell, J. The Concept of Energy Security: Beyond the Four As. *Energy Policy* **2014**, *75*, 415–421. [CrossRef]
23. Lewandowski, M. Bezpieczeństwo energetyczne w problematyce bezpieczeństwa narodowego. *De Secur. Et Defensione. O Bezpieczeństwie I Obron.* **2019**, *1*, 168–185. (In Polish) [CrossRef]
24. Sutrisno, A.; Normaler, Ö.; Alkemade, F. Has the global expansion of energy markets truly improved energy security? *Energy Policy* **2021**, *148*, 111931. [CrossRef]
25. Prohorovs, A. Russia's War in Ukraine: Consequences for European Countries' Businesses and Economies. *J. Risk Financ. Manag.* **2022**, *15*, 295. [CrossRef]

26. Escobar, J.A.; Lora, E.E.; Venturini, O.J.; Yáñez, E.; Castillo, E.F.; Almazán, O. Biofuels: Environment, technology and food security. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1275–1287. [CrossRef]
27. Hirani, A.A.; Javed, N.; Asif, M.; Basu, S.K.; Kumar, A. A Review on First- and Second-Generation Biofuel Productions. In *Biofuels: Greenhouse Gas Mitigation and Global Warming*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 141–154.
28. Bielski, S.; Zielińska-Chmielewska, A.; Marks-Bielska, R. Use of Environmental Management Systems and Renewable Energy Sources in Selected Food Processing Enterprises in Poland. *Energies* **2021**, *14*, 3212. [CrossRef]
29. Oladosu, G.; Msangi, S. Biofuel-Food Market Interactions: A Review of Modeling Approaches and Findings. *Agriculture* **2013**, *3*, 53–71. [CrossRef]
30. Godfray, C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. Food security: The challenge of feeding 9 billion people. *Science* **2010**, *327*, 812–818. [CrossRef]
31. Koizumi, T. Biofuel and food security in China and Japan. *Renew. Sustain. Energy Rev.* **2013**, *21*, 102–109. [CrossRef]
32. House of Commons Environmental Audit Committee. Are Biofuels Sustainable? First Report of Session 2007–2008. 2008; Volume 1, p. 16. Available online: <https://publications.parliament.uk/pa/cm200708/cmselect/cmenvaud/76/76.pdf> (accessed on 9 September 2025).
33. Marks-Bielska, R.; Bielski, S.; Novikova, A.; Romaneckas, K. Straw stocks as a source of renewable energy. A case study of a district in Poland. *Sustainability* **2019**, *11*, 4714. [CrossRef]
34. Jacobus, A.P.; Gross, J.; Evans, J.H.; Ceccato-Antonini, S.R.; Gombert, A.K. *Saccharomyces cerevisiae* strains used industrially for bioethanol production. *Essays Biochem.* **2021**, *65*, 147–161. [CrossRef]
35. Altieri, M.A. The ecological impacts of large-scale agrofuel monoculture production systems in the Americas. *Bull. Sci. Technol. Soc.* **2009**, *29*, 236–244. [CrossRef]
36. Zakari, A.; Toplak, J.; Tomažič, L.M. Exploring the Relationship between Energy and Food Security in Africa with Instrumental Variables Analysis. *Energies* **2022**, *15*, 5473. [CrossRef]
37. Geddes, C.C.; Nieves, I.U.; Ingram, L.O. Advances in ethanol production. *Curr. Opin. Biotechnol.* **2011**, *22*, 312–319. [CrossRef]
38. Tilman, D.G.; Socolow, R.; Foley, J.A.; Hill, J.; Larson, E.; Lynd, L.; Pacala, S.; Reilly, J.; Searchinger, T.; Somerville, C.; et al. Beneficial biofuels—The food, energy, and environment trilemma. *Science* **2009**, *325*, 270–271. [CrossRef]
39. Gutierrez, A.P.; Ponti, L. Bioeconomic sustainability of cellulosic biofuel production on marginal lands. *Bull. Sci. Technol. Soc.* **2009**, *29*, 213–225. [CrossRef]
40. Ravindranath, N.H.; Sita Lakshmi, C.; Manuvie, R.; Balachandra, P. Biofuel production and implications for land use, food production and environment in India. *Energy Policy* **2011**, *39*, 5737–5745. [CrossRef]
41. Meka, P.K.; Tripathi, V.; Singh, R.P. Synthesis of biodiesel fuel from safflower oil using various reaction parameters. *J. Oleo Sci.* **2007**, *56*, 9–12. [CrossRef]
42. Miao, X.; Wu, Q. Biodiesel production from heterotrophic microalgal oil. *Bioresour. Technol.* **2006**, *97*, 841–846. [CrossRef]
43. Carraretto, C.; Macor, A.; Mirandola, A.; Stoppato, A.; Tonon, S. Biodiesel as alternative fuel: Experimental analysis and energetic evaluations. *Energy* **2004**, *29*, 2195–2211. [CrossRef]
44. Demirbaş, A. Diesel fuel from vegetable oil via transesterification and soap pyrolysis. *Energy Source.* **2002**, *24*, 835–841. [CrossRef]
45. Shahid, E.M.; Jamal, Y. Production of biodiesel: A technical review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4732–4745. [CrossRef]
46. Chhetri, A.B.; Islam, M.R. Towards producing a truly green biodiesel. *Energy Sources Part A Recovery Util. Environ. Eff.* **2008**, *30*, 754–764. [CrossRef]
47. Van Gerpen, J. Biodiesel processing and production. *Fuel Process. Technol.* **2005**, *86*, 1097–1107. [CrossRef]
48. IRENA. 2024. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf?utm_source=chatgpt.com (accessed on 3 November 2025).
49. Agyekum, E.B.; Okonkwo, P.C.; Rashid, F.L. Research on biomass energy and CO₂ conversion to methanol: A combination of conventional and bibliometric review analysis. *Carbon Res.* **2025**, *4*, 4. [CrossRef]
50. Haas, M.J.; Foglia, T.A. Alternate feed stocks and technologies for biodiesel production. In *Biodiesel Handbook*; Knothe, G., Krahl, J., Gerpen, J.V., Eds.; AOCS Press: Urbana, IL, USA, 2005; pp. 42–61.
51. Susanne, R.S. Making the best of wastewater. *Biodiesel Magazine*, 2008, p. 16. Available online: <http://www.biodieselmagazine.com/articles/2776/making-the-best-of-wastewater> (accessed on 9 September 2025).
52. Mondala, A.; Liang, K.; Toghiani, H.; Hernandez, R.; French, T. Biodiesel production by in situ transesterification of municipal primary and secondary sludges. *Bioresour. Technol.* **2009**, *100*, 1203–1210. [CrossRef]
53. Revellame, E.; Hernandez, R.; French, W.; Holmes, W.; Alley, E.; Callahan, R. II Production of biodiesel from wet activated sludge. *J. Chem. Technol. Biotechnol.* **2011**, *86*, 61–68. [CrossRef]
54. Sharma, P.; Usman, M.; Salama, E.S.; Redina, M.; Thakur, N.; Li, X. Evaluation of various waste cooking oils for biodiesel production: A comprehensive analysis of feedstock. *Waste Manag.* **2021**, *136*, 219–229. [CrossRef] [PubMed]
55. Yusuf, B.O.; Oladepo, S.A.; Ganiyu, S.A. Biodiesel production from waste cooking oil via β -zeolite-supported sulfated metal oxide catalyst systems. *ACS Omega* **2003**, *8*, 23720–23732. [CrossRef] [PubMed]

56. Vyas, A.P.; Verma, J.L.; Subrahmanyam, N. A review on FAME production processes. *Fuel* **2010**, *89*, 1–9. [\[CrossRef\]](#)
57. Hall, C.A.S.; Balogh, S.; Murphy, D.J.R. What is the minimum EROI that a sustainable society must have? *Energies* **2009**, *2*, 25–47. [\[CrossRef\]](#)
58. Hall, C.A.S.; Lambert, J.G.; Balogh, S.B. EROI of different fuels and the implications for society. *Energy Policy* **2014**, *64*, 141–152. [\[CrossRef\]](#)
59. Gomiero, T. Are biofuels an effective and viable energy strategy for industrialized societies? A reasoned overview of potentials and limits. *Sustainability* **2015**, *7*, 8491–8521. [\[CrossRef\]](#)
60. Murphy, D.J.; Rauegi, M.; Carbajales-Dale, M.; Rubio Estrada, B. Energy Return on Investment of Major Energy Carriers: Review and Harmonization. *Sustainability* **2022**, *14*, 7098. [\[CrossRef\]](#)
61. Arshad, M.; Mohanty, A.K.; Van Acker, R.; Riddle, R.; Todd, J.; Khalil, H.; Misra, M. Valorization of camelina oil to biobased materials and biofuels for new industrial uses: A review. *RSC Adv.* **2022**, *12*, 27230–27245. [\[CrossRef\]](#)
62. Bouter, A.; Duval-Dachary, S.; Besseau, R. Life cycle assessment of liquid biofuels: What does the scientific literature tell us? A statistical environmental review on climate change. *Biomass Bioenergy* **2024**, *190*, 107418. [\[CrossRef\]](#)
63. Papagianni, S.; Capellán-Pérez, I.; Adam, A.; Pastor, A. Review and meta-analysis of Energy Return on Investment and environmental indicators of biofuels. *Renew. Sustain. Energy Rev.* **2024**, *203*, 114737. [\[CrossRef\]](#)
64. Malik, K.; Capareda, S.C.; Kamboj, B.R.; Malik, S.; Singh, K.; Arya, S.; Bishnoi, D.K. Biofuels production: A review on sustainable alternatives to traditional fuels and energy sources. *Fuels* **2024**, *5*, 157–175. [\[CrossRef\]](#)
65. Kardan, A.; Gilani, N.; Mottaghtalab, V. From CO₂ to methanol: A comprehensive analysis of carbon, semiconductor, and mof-based catalysts. *Iran. J. Chem. Chem. Eng.* **2024**, *43*, 3701–3736.
66. Duque, A.; Álvarez, C.; Doménech, P.; Manzanares, P.; Moreno, A.D. Advanced Bioethanol Production: From Novel Raw Materials to Integrated Biorefineries. *Processes* **2021**, *9*, 206. [\[CrossRef\]](#)
67. Satari, B.; Karimi, K.; Kumar, R. Cellulose solvent based pretreatment for enhanced second—Generation biofuel production: A review. *Sustain. Energy Fuels* **2019**, *3*, 11–62. [\[CrossRef\]](#)
68. Manocchio, C.; Andrade, B.R.; Rodriguez, R.P.; Moraes, B.S. Ethanol from biomass: A comparative overview. *Renew. Sustain. Energy Rev.* **2017**, *80*, 743–755. [\[CrossRef\]](#)
69. Linoj, K.N.V.; Dhavala, P.; Goswami, A.; Maithel, S. Liquid biofuels in South Asia: Resources and technologies. *Asian Biotechnol. Dev. Rev.* **2006**, *8*, 31–49. Available online: https://ris.org.in/sites/default/files/article3_v8n2.pdf (accessed on 9 September 2025).
70. Yang, H.; Lv, Y.; Wang, L.; Shen, L. The ecology risk of large scale planation of energy crops in China. *J. Anhui Agric. Sci.* **2012**, *40*, 13941–14151.
71. Rubin, E.M. Genomics of cellulosic biofuels. *Nature* **2008**, *454*, 841–845. [\[CrossRef\]](#)
72. Rastogi, M.; Shrivastava, S. Recent advances in second generation bioethanol production: An insight to pretreatment, saccharification and fermentation processes. *Renew. Sustain. Energy Rev.* **2017**, *80*, 330–340. [\[CrossRef\]](#)
73. Galbe, M.; Zacchi, G. A review of the production of ethanol from softwood. *Appl. Microbiol. Biotechnol.* **2002**, *59*, 618–628. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Tilman, D.; Hill, J.; Lehman, C. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **2006**, *314*, 1598–1600. [\[CrossRef\]](#)
75. Sims, R.E.; Mabee, W.; Saddler, J.N.; Taylor, M. An overview of second generation biofuel technologies. *Bioresour. Technol.* **2010**, *101*, 1570–1580. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Wilhelm, W.W.; Johnson, J.M.F.; Karlen, D.L.; Lightle, D.T. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agron. J.* **2007**, *99*, 1665–1667. [\[CrossRef\]](#)
77. Blanco-Canqui, H.; Lal, R.; Post, W.P.; Owens, L.B. Changes in long-term no-till corn growth and yield under different rates of stover mulch. *Agron. J.* **2006**, *98*, 1128–1136. [\[CrossRef\]](#)
78. Wang, X.; He, C.; Liu, B.; Zhao, X.; Liu, Y.; Wang, Q.; Zhang, H. Effects of residue returning on soil organic carbon storage and sequestration rate in China’s croplands: A meta-analysis. *Agronomy* **2020**, *10*, 691. [\[CrossRef\]](#)
79. Blanco-Canqui, H.; Lal, R. Crop Residue Removal Impacts on Soil Productivity and Environmental Quality. *Crit. Rev. Plant Sci.* **2009**, *28*, 139–163. [\[CrossRef\]](#)
80. Lin, B.J.; Li, R.C.; Liu, K.C.; Pelumi Oladele, O.; Xu, Z.Y.; Lal, R.; Zhao, X.; Zhang, H.L. Management--induced changes in soil organic carbon and related crop yield dynamics in China’s cropland. *Glob. Change Biol.* **2023**, *29*, 3575–3590. [\[CrossRef\]](#)
81. Huang, H.J.; Ramaswamy, S.; Al Dajani, W.; Tschirner, U.; Cairncross, R.A. Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. *Biomass Bioenerg.* **2009**, *33*, 234–246. [\[CrossRef\]](#)
82. Bhaskar, T.; Bhavya, B.; Singh, R.; Naik, D.V.; Kumar, A.; Goyal, H.B. Thermochemical conversion of biomass to biofuels. In *Biofuels—Alternative Feedstocks and Conversion Processes*; Pandey, A., Larroche, C., Ricke, S.C., Dussap, C.G., Gnansounou, E., Eds.; Academic Press: Oxford, UK, 2011; pp. 51–77. [\[CrossRef\]](#)

83. Kumar, R.; Tabatabaei, M.; Karimi, K.; Horváth, I.S. Recent updates on lignocellulosic biomass derived ethanol—A review. *Biofuel Res. J.* **2016**, *9*, 347–356. [CrossRef]
84. Ferreira-Leitao, V.; Gottschalk, L.M.F.; Ferrara, M.A.; Nepomuceno, A.L.; Molinari, H.B.C.; Bon, E.P.S. Biomass residues in Brazil: Availability and potential uses. *Waste Biomass Valoriz.* **2010**, *1*, 65–76. [CrossRef]
85. Warner, E.; Moriarty, K.; Lewis, J.; Milbrandt, A.; Schwab, A. *2015 Bioenergy Market Report*; National Renewable Energy Laboratory: Golden, CO, USA, 2015. Available online: <https://www.nrel.gov/docs/fy17osti/66995.pdf> (accessed on 9 September 2025).
86. Demirbaş, M.F.; Balat, M.; Balat, H. Potential contribution of biomass to the sustainable energy development. *Energy Convers. Manag.* **2009**, *50*, 1746–1760. [CrossRef]
87. Ericsson, K.; Nilsson, L.J. Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass Bioenergy* **2006**, *30*, 1–15. [CrossRef]
88. Nizami, A.; Murphy, J.D. What type of digester configurations should be employed to produce biomethane from grass silage? *Renew. Sustain. Energy Rev.* **2010**, *14*, 1558–1568. [CrossRef]
89. Richards, K.; Richardson, J.; Saddler, J.; Smith, T.; Popescu, O. Biofuels and bioenergy: Challenges and opportunities. *Biomass Bioenergy* **2006**, *35*, 4495–4496. [CrossRef]
90. Bušić, A.; Marđetko, N.; Kundas, S.; Morzak, G.; Belskaya, H.; Ivančić Šantek, M.; Komes, D.; Novak, S.; Šantek, B. Bioethanol production from renewable raw materials and its separation and purification: A Review. *Food. Technol. Biotechnol.* **2018**, *56*, 289–311. [CrossRef] [PubMed]
91. Renewable Fuels Association (RFA). Available online: <https://ethanolrfa.org/markets-and-statistics/annual-ethanol-production> (accessed on 3 November 2025).
92. ePURE. European Renewable Ethanol—Key Figures 2023/2024. Available online: <https://www.epure.org/wp-content/uploads/2025/09/250908-DEF-PR-European-renewable-ethanol-Key-figures-2024.pdf> (accessed on 3 November 2025).
93. UNICA/USD FAS. Biofuels Annual. Available online: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels+Annual_Brasilia_Brazil_BR2024-0022.pdf (accessed on 3 November 2025).
94. World Bioenergy Association (WBA)/REN21/IEA. Available online: <https://www.worldbioenergy.org/uploads/WBA%20Global%20Bioenergy%20Statistics%202015.pdf> (accessed on 3 November 2025).
95. FAO/OECD/USDA. Biofuels Annual. Available online: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=biofuels+annual_the+hague_eu-28_7-15-2015.pdf (accessed on 3 November 2025).
96. Pimentel, D.; Patzek, T. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Nat. Resour. Res.* **2005**, *14*, 65–76. [CrossRef]
97. Koh, L.P.; Ghazoul, J. Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities. *Biol. Conserv.* **2008**, *141*, 2450–2460. [CrossRef]
98. Demirbaş, A. *Biofuels: Securing the Planet's Future Energy Needs*; Springer: London, UK, 2009. [CrossRef]
99. Marks-Bielska, R.; Bielski, S.; Kurowska, K.; Kryszk, H. Potential ability to increase the area of winter rapeseed cultivation for biofuel production in Poland. *Proc. Eng. Rural. Dev.* **2015**, *14*, 330–335. Available online: http://www.tf.llu.lv/conference/proceedings2015/Papers/054_Marks-Bielska.pdf (accessed on 9 September 2025).
100. Giampietro, M.; Mayumi, K. *The Biofuel Delusion: The Fallacy of Large Scale Agro-Biofuels Production*; Earthscan: London, UK, 2009.
101. Chiaramonti, D.; Recchia, L. Is life cycle assessment (LCA) a suitable method for quantitative CO₂ saving estimations? The impact of field input on the LCA results for a pure vegetable oil chain. *Biomass Bioenergy* **2010**, *34*, 787–797. [CrossRef]
102. Ridley, C.E.; Clark, C.M.; LeDuc, S.D.; Bierwagen, B.G.; Lin, B.B.; Mehl, A.; Tobias, D.A. Biofuels: Network analysis of the literature reveals key environmental and economic unknowns. *Environ. Sci. Technol.* **2012**, *46*, 1309–1315. [CrossRef]
103. Searchinger, T.; Edwards, R.; Mulligan, D.; Heimlich, R.; Plevin, R. Do biofuel policies seek to cut emissions by cutting food? *Science* **2015**, *15*, 1420–1422. [CrossRef] [PubMed]
104. Farigione, J.; Hill, J.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **2008**, *319*, 1235–1238. [CrossRef]
105. Altieri, M.A.; Bravo, E. The Ecological and Social Tragedy of Crop-Based Biofuel Production in the Americas. 2007. Available online: https://pdfs.semanticscholar.org/79d6/6ccf6a5dbb66ca68e633a385be0514022fde.pdf?_ga=2.85671385.1775323319.1572984889-809263266.1563614110 (accessed on 9 September 2025).
106. Li, K.; Liu, S.; Liu, X. An overview of algae bioethanol production. *Int. J. Energy Res.* **2014**, *38*, 965–977. [CrossRef]
107. Agarwal, A.K. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Prog. Energy. Combust.* **2007**, *33*, 233–271. [CrossRef]
108. Charles, C.; Gerasimchuk, I.; Bridle, R.; Moerenhout, T.; Asmelash, E.; Laan, T. *Biofuels—At What Cost? A Review of Costs and Benefits of EU Biofuel Policies*; The International Institute for Sustainable Development: Geneva, Switzerland, 2013. Available online: https://www.iisd.org/gsi/sites/default/files/biofuels_subsidies_eu_review.pdf (accessed on 9 September 2025).
109. Lopez, G.P.; Laan, T. *Biofuels—At What Cost? Government Support for Biodiesel in Malaysia*; The International Institute for Sustainable Development: Geneva, Switzerland, 2009. Available online: https://www.iisd.org/system/files/publications/biofuels_subsidies_malaysia.pdf (accessed on 9 September 2025).

110. Wang, Q.; Tian, Z. Biofuels and the policy implications for China. *Asian-Pac. Econ. Lit.* **2011**, *25*, 161–168. [CrossRef]
111. Daniel, R.; Lebel, L.; Gheewala, S.H. Agrofueles in Thailand: Policies, practices and prospects. In *Sustainable Production Consumption Systems: Knowledge, Engagement and Practice*; Lebel, L., Lorek, S., Daniel, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; pp. 97–122. [CrossRef]
112. Murphy, D.J.; Hall, C.A.S. Year in review—EROI or energy return on (energy) invested 2010. *Ann. N. Y. Acad. Sci.* **2010**, *1185*, 102–118. [CrossRef]
113. Patzek, T. Thermodynamics of the corn-ethanol biofuel cycle. *Crit. Rev. Plant. Sci.* **2004**, *23*, 519–567. [CrossRef]
114. Bielski, S.; Jankowski, K.; Budzyński, W. The energy efficiency of oil seed crops production and their biomass conversion into liquid fuels. *Przem. Chem.* **2014**, *93/12*, 2270–2273. (In Polish)
115. Bielski, S.; Romanekas, K.; Novikova, A.; Šarauskis, E. Are higher input levels to triticale growing technologies effective in biofuel production system? *Sustainability* **2019**, *11*, 5915. [CrossRef]
116. Arodudu, O.; Helming, K.; Wiggering, H.; Voinov, A. Bioenergy from low-intensity agricultural systems: An energy efficiency analysis. *Energies* **2017**, *10*, 29. [CrossRef]
117. Donke, A.; Nogueira, A.; Matai, P.; Kulay, L. Environmental and energy performance of ethanol production from the integration of sugarcane, corn, and grain sorghum in a multipurpose plant. *Resources* **2016**, *6*, 1. [CrossRef]
118. McPhail, L.L.; Babcock, B.A. Impact of US biofuel policy on US corn and gasoline price variability. *Energy* **2012**, *37/1*, 505–513. [CrossRef]
119. de Gorter, H.; Drabik, D.; Just, D.R. Biofuel policies and food grain commodity prices 2006–2012: All boom and no bust? *Ag. Bio. Forum* **2013**, *16*, 1–13. Available online: <https://agbioforum.org/wp-content/uploads/2021/02/AgBioForum-16-1-1.pdf> (accessed on 9 September 2025).
120. Tyner, W.E.; Taheripour, F.; Hurt, C. *Potential Impacts of a Partial Waiver of the Ethanol Blending Rules*; Oak Brook: Farm Foundation, IL, USA, 2012; pp. 1–13. Available online: https://www.alimenterre.org/system/files/ressources/pdf/388-purdue_paper_final.pdf (accessed on 9 September 2025).
121. Helbling, T.; Mercer-Blackman, V.; Cheng, K. Riding a Wave. *Financ. Dev.* **2008**, *45*, 10–15. Available online: <https://www.imf.org/external/pubs/ft/fandd/2008/03/pdf/helbling.pdf> (accessed on 9 September 2025).
122. Hamulczuk, M. Biofuel policy and agricultural commodity prices—Selected issues. *Roczniki Naukowe SERiA* **2014**, *16*, 82–87. Available online: <https://rnseria.com/resources/html/article/details?id=172658> (accessed on 9 September 2025). (In Polish)
123. Serra, T.; Zilberman, D.; Gil, J.M.; Goodwin, B.K. Nonlinearities in the U.S. corn-ethanol-oilgasoline price system. *Agric. Econ.* **2011**, *42*, 35–45. [CrossRef]
124. Cotula, L.; Dyer, N.; Vermeulen, S. *Fuelling Exclusion? The Biofuels Boom and Poor People's Access to Land*; International Institute for Environment and Development: London, UK, 2008. Available online: <http://pubs.iied.org/pdfs/12551IIED.pdf> (accessed on 9 September 2025).
125. Creutzig, F.; Corbera, E.; Bolwig, S.; Hunsberger, C. Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environ. Res. Lett.* **2013**, *8*, 1–11. [CrossRef]
126. Obidzinski, K.; Andriani, R.; Komarudin, H.; Andrianto, A. Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecol. Soc.* **2012**, *17*, 25. [CrossRef]
127. Bindraban, P.S.; Bulte, E.H.; Conijn, S.G. Can large-scale biofuels production be sustainable by 2020? *Agric. Syst.* **2009**, *101*, 197–199. [CrossRef]
128. Robertson, G.P.; Gross, K.L.; Hamilton, S.K.; Landis, D.A.; Schmidt, T.M.; Snapp, S.S.; Swinton, S.M. Farming for ecosystem services: An ecological approach to production agriculture. *Bioscience* **2012**, *64*, 404–415. [CrossRef]
129. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Is there a need for a more sustainable agriculture? *Crit. Rev. Plant Sci.* **2011**, *30*, 6–23. [CrossRef]
130. Quintarelli, V.; Radicetti, E.; Allevato, E.; Stazi, S.R.; Haider, G.; Abideen, Z.; Bibi, S.; Jamal, A.; Mancinelli, R. Cover crops for sustainable cropping systems: A review. *Agriculture* **2022**, *12*, 2076. [CrossRef]
131. Von Cossel, M.; Scordia, D.; Altieri, M.; Gresta, F. Spotlight on agroecological cropping practices to improve the resilience of farming systems: A qualitative review of meta-analytic studies. *Front. Agron.* **2025**, *7*, 1495846. [CrossRef]
132. Crutzen, P.J.; Mosier, A.R.; Smith, K.A.; Winiwarter, W. N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys. Discuss.* **2007**, *7*, 11191–11205. [CrossRef]
133. Robertson, G.P.; Dale, V.H.; Doering, O.C.; Hamburg, S.P.; Melillo, J.M.; Wander, M.M.; Parton, W.J.; Adler, P.R.; Barney, J.N.; Cruse, R.M.; et al. Agriculture. Sustainable biofuels redux. *Science* **2008**, *322*, 49–50. [CrossRef]
134. OECD-FAO. Agricultural Outlook. Available online: https://stats.oecd.org/Index.aspx?datasetcode=HIGH_AGLINK_2019# (accessed on 9 September 2025).
135. Szajner, P. (Ed.) *World Biofuel Production in the Context of Food Security*; Wyd. IEiGŻ Warszawa: Warszawa, Poland, 2013. Available online: <https://open.icm.edu.pl/items/c65be717-41fa-45c4-9819-80b6179d3ea3> (accessed on 9 September 2025). (In Polish)
136. Phan, A.N.; Phan, T.M. Biodiesel production from waste cooking oils. *Fuel* **2008**, *87*, 3490–3496. [CrossRef]

137. Cafaro, V.; Testa, G.; Patanè, C. Castor: A Renewed Oil Crop for the Mediterranean Environment. *Agronomy* **2025**, *15*, 1402. [[CrossRef](#)]
138. Angelini, L.G.; Abou Chehade, L.; Foschi, L.; Tavarini, S. Performance and potentiality of camelina (*Camelina sativa* L. Crantz) genotypes in response to sowing date under Mediterranean environment. *Agronomy* **2020**, *10*, 1929. [[CrossRef](#)]
139. Yan, J.; Zheng, X.; Li, S. A novel and robust recombinant *Pichia pastoris* yeast whole cell biocatalyst with intracellular over expression of a *Thermomyces lanuginosus* lipase: Preparation, characterization and application in biodiesel production. *Bioresour. Technol.* **2014**, *151*, 43–48. [[CrossRef](#)] [[PubMed](#)]
140. Bobadilla, M.C.; Lorza, R.L.; García, R.E.; Gómez, F.S.; González, E.P.V. An improvement in biodiesel production from waste cooking oil by applying thought multi-response surface methodology using desirability functions. *Energies* **2017**, *10*, 30. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.