Biofuel as a Renewable Energy: Potential, Technology, and Challenges Towards a Sustainable Energy Transition

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***Abstract*—Biofuel is a promising renewable energy alternative to reduce dependence on fossil fuels and lower greenhouse gas emissions. This article presents a comprehensive overview of biofuel classification (generation I–IV and physical forms), production technologies (fermentation, transesterification, gasification, pyrolysis), and the applications of bioethanol, biodiesel, and biogas in the transportation, industrial, and power generation sectors. Energy efficiency and environmental impact analyses are conducted using a life cycle assessment (LCA) approach, while national energy policies are examined in the Indonesian context, including the mandatory blending program (B30–B50) and sustainability strategies. While biofuels have significant potential, challenges such as production efficiency, land conflicts, and regulatory consistency need to be addressed for biofuels to truly contribute to the national energy transition.**

Keywords*—Biofuel, Renewable Energy, Biodiesel, Bioethanol, Microalgae, Indonesian Energy Policy*

I. INTRODUCTION

Global dependence on fossil fuels has had serious environmental, economic, and social consequences. The industrial and transportation sectors are major contributors to carbon dioxide (CO_2) emissions, which accelerate global warming [1]. Furthermore, fossil fuels are limited and geographically uneven, threatening global energy security. The transition to renewable energy is an urgent need to achieve long-term sustainability. One promising energy source is biofuel, a naturally renewable fuel derived from biomass [2]. In the Indonesian context, biofuel plays a significant role in national energy policy through the mandatory biodiesel program (B30, B35, and B40) as part of the energy diversification strategy [3]. This article aims to review the development of biofuels from the aspects of technology, energy efficiency, environmental impact, as well as policy and implementation challenges in Indonesia.

II. METHODS

This research is a literature review with a narrative approach that focuses on the latest research results (2015–2025). Literature sources were obtained from scientific databases such as ScienceDirect, Springer, IEEE Xplore, and reports from international institutions (IEA, IPCC). Literature selection was carried out based on relevance to the biofuel theme, which includes classification, production processes, efficiency, and energy policy. The analysis was conducted descriptively and critically to synthesize the development of biofuel technology and its relevance to Indonesia's national conditions.

III. CLASSIFICATION AND CHARACTERISTICS OF BIOFUELS

Biofuels are classified into four generations based on their raw material sources and production technology. The first generation comes from food crops such as sugarcane and corn; the second generation from non-food biomass such as straw and wood waste; the third generation from microalgae; and the fourth generation uses genetic engineering and CO_2 absorption technology [4]. Based on their physical form, biofuels can be liquid (bioethanol, biodiesel), gas (biogas, biohydrogen), and solid (biomass briquettes, biochar). Each has different characteristics and efficiency in energy conversion [5].

VI. CLASSIFICATION AND CHARACTERISTICS OF BIOFUELS

Biofuels are produced through various biochemical and thermochemical processes tailored to the type of raw material. The four main pathways are fermentation, transesterification, pyrolysis, and gasification. Each has different technical characteristics, energy yields, and environmental impacts.

4.1 Fermentation Process

Fermentation is the conversion of carbohydrates into bioethanol using microorganisms such as Saccharomyces cerevisiae. The general reaction is $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$. This process involves a pretreatment stage to break down lignocellulose, enzymatic hydrolysis to produce glucose, and alcoholic fermentation. The conversion efficiency of sugarcane and corn can reach 90%, producing bioethanol with a content of 96% after distillation. In Brazil, the energy efficiency of sugarcane bioethanol reaches 8.3 MJ/MJ input, while in Indonesia, the average is 5.6 MJ/MJ [4], [6].

4.2 Transesterification Process

Transesterification is a chemical reaction between triglycerides (from vegetable oils or animal fats) and short-chain alcohols (methanol or ethanol) using a base catalyst (NaOH, KOH) to produce esters (biodiesel) and glycerol. General reaction: Triglycerides + $3CH_3OH \rightarrow 3RCOOCH_3 + C_3H8O_3$. This process takes place at a temperature of 60°C and atmospheric pressure for 1–2 hours. Biodiesel yield can reach 98% if the FFA content is low (<1%). In Indonesia, palm oil, used cooking oil, and jatropha curcas are the main raw materials with production costs of around Rp7,000–9,000/liter [5], [14].

4.3 Pyrolysis and Gasification Process

Pyrolysis decomposes biomass at a temperature of 400–600°C in the absence of oxygen to produce three main fractions: bio-oil (60–70%), biochar (15–25%), and gas (10–20%). Bio-oil has a calorific value of 16–19 MJ/kg and can be further processed into liquid fuel. Gasification heats biomass at 800–1000°C with limited oxygen supply, producing synthesis gas (syngas) consisting of CO, H_2, CH_4, and CO_2. Gasification energy efficiency can reach 75–85% [7], [8].

4.4 Biofuel Applications

Liquid biofuels are used in motor vehicles, diesel power plants, and co-firing systems in coal-fired power plants. Bioethanol can be blended up to 20% with gasoline (E20) without engine modification. Biodiesel is used up to 35% of the blend (B35) in Indonesia. Gaseous biofuels (biogas, syngas) are used in CHP (Combined Heat and Power) reactors with a thermal efficiency of 85%. Solid biofuels such as biochar are used as solid fuels and as carbon stabilizers in soil [9], [10]. Table 1 compares the efficiency and environmental impact of biofuels to fossil fuels.

Table 1. Efficiency and environmental impact of biofuels compared to fossil fuels

Fuel Type	Energy Efficiency (%)	CO_2 Emission (kg/L)	Feedstock Source	Sustainability Status
Diesel (fossil)	35–40	2.7	Crude oil	Non-renewable
Biodiesel	40–45	1.2–1.5	Vegetable oil	Renewable
Bioethanol	30–35	1.0–1.3	Sugarcane, Corn	Renewable
Biogas	60–70	0.8–1.0	Organic waste	Renewable

V. EFFICIENCY AND ENVIRONMENTAL IMPACT ANALYSIS

5.1 Energy Analysis and LCA

The energy efficiency of biofuels is measured by the ratio of energy output to input (EROI). The EROI value of sugarcane bioethanol reaches 8, while palm biodiesel is around 3–4 [11]. Life Cycle Assessment (LCA) shows a reduction in CO_2 emissions of up to 70–90% compared to conventional diesel [12]. Land and fertilizer use have a significant impact on total life cycle emissions. The IEA study (2024) estimates that global biodiesel use has the potential to reduce 1.8 gigatons of CO_2 by 2050 if implemented massively [11].

5.2 Air Quality and Ecosystem Impacts

Biofuels reduce particulate matter (PM2.5), NOx, and SO_2 emissions by up to 30% compared to diesel [13]. However, palm oil land conversion causes the loss of 0.5–1.0 million hectares of tropical forest per decade in Southeast Asia [12]. Bioethanol production from agricultural waste and microalgae can reduce land pressure by up to 40% compared to food [18].

5.3 Sustainability Aspects

Sustainability factors include net emissions, land conservation, and socio-economic value. Third–fourth generation microalgae-based biofuels have 30 times higher productivity per hectare than palm oil [19]. Microalgae also absorb up to 1.8 tons of CO_2 per ton of dry biomass. Research by Zhang et al. (2024) shows that the integrated biofuel–microalgae–organic fertilizer system can save 20% of total energy compared to conventional systems [8].

VI. ECONOMIC ASPECTS AND ENERGY POLICY IN INDONESIA

6.1 National Biofuel Economic Structure

The Indonesian biodiesel industry is supported by CPO (crude palm oil), whose production reaches 45 million tons per year. Around 20% is used for domestic biodiesel [14]. The cost of biodiesel production reaches IDR 8,000/liter with an average subsidy of IDR 1,500/liter. Biodiesel export revenues are expected to reach USD 3.5 billion in 2024. However, dependence on CPO causes fluctuations in raw material prices [15]. Diversification of raw materials, such as used cooking oil and jatropha curcas, is a solution for supply stability.

6.2 Energy Policy and Green Transition

The government's main policies include RUEN (National Energy General Plan), Presidential Decree No. 112 of 2022 concerning Renewable Energy, and the B35 mandate. The government targets a renewable energy contribution of 23% by 2025 and 31% by 2050 [16], [21]. The BPDPKS program funds biodiesel incentives and green energy research. However, large subsidies (more than IDR 40 trillion/year) create fiscal pressure [17]. To overcome this, emission-based subsidy reform (carbon pricing) and biofuel integration in the carbon market are needed.

6.3 Social and Environmental Impacts

Biofuels create jobs for 1.2 million workers in the agricultural and processing sectors [15]. However, strict regulations are needed to ensure that palm oil expansion does not compromise food security. Village biogas development (the BIRU program) has saved 1.3 million tons of CO_2/year and increased local energy security [20]. With collaboration between government, academia, and industry, the biofuel energy transition can strengthen Indonesia's green economy.

VII. GLOBAL CHALLENGES AND FUTURE DEVELOPMENT DIRECTIONS

The main challenges in biofuel development include land-based conflicts, technological efficiency, and infrastructure limitations [18]. Next-generation biofuels, such as those based on microalgae and genetic engineering, offer sustainable solutions without disrupting the food chain [19]. The integration of a circular economy into biofuel systems allows the use of agricultural and industrial waste as energy feedstock [20]. International policy support, research, and investment are key factors for the success of the transition to a bioenergy-based green economy [21].

VI. CONCLUSION

Biofuels hold significant potential as a renewable energy source to reduce dependence on fossil fuels and lower carbon emissions. Through technological innovation and consistent policy support, biofuels can play a significant role in the national energy transition. However, a comprehensive approach to land management, increased production efficiency, and enhanced next-generation research are needed to ensure truly sustainable biofuel use.

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