Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Techno-economic Assessment of Biofuel Utilization and Waste-to-Energy Systems for the Sustainable Energy Transition

**Athanasios Dounavis**

adounavis@uowm.gr

University of Western Macedonia: Panepistemio Dytikes Makedonias

**Gerasimoula Alexopoulou**

University of Western Macedonia: Panepistemio Dytikes Makedonias

**Research Article**

**Keywords:** Biofuels, Biodiesel, Transesterification, Marine Fuels, Waste-to-Energy, Techno-economic assessment, Anaerobic digestion

**Posted Date:** June 2nd, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-9107549/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

## Abstract

The global dependence on fossil fuels has led to severe environmental and economic pressures, while the gradual exhaustion of conventional energy sources highlights the urgent demand for sustainable alternatives. Biofuels, particularly biodiesel, offer a promising solution due to their lower emissions, superior combustion performance, and environmental advantages compared to traditional fossil fuels. This study provides a comprehensive assessment of current biodiesel production worldwide, examining the range of feedstocks, production techniques, and key techno-economic factors, with a special focus on renewable and waste-derived raw materials. Furthermore, the study evaluates biodiesel's potential role in the maritime sector, considering regulatory requirements, fuel price volatility, and energy security challenges. Recent global disruptions, including the COVID-19 pandemic and the energy crisis amplified by the Russia–Ukraine conflict, have driven unprecedented increases in fuel prices, significantly impacting energy-intensive industries such as shipping. The findings underscore the importance of diversifying fuel supply chains and enhancing energy resilience. With appropriate policy measures, availability of feedstocks, and technological optimization, biodiesel could substantially reduce emissions and stabilize fuel costs in maritime transport, reinforcing its role as a transitional fuel within broader decarbonization strategies.


# 1. INTRODUCTION

Biofuels have been explored as a supplementary alternative to conventional fossil fuels in the transportation sector since the oil crises of the 1970s. At the turn of the 21st century, interest in biofuels resurged, driven by growing concerns over climate change, the gradual depletion of fossil fuel reserves, and the increasing volatility of crude oil prices. Today, over 40 countries worldwide have implemented national policies to support the promotion and development of biofuels (Timilsina, 2014).

Despite their recognition as a cleaner energy option aimed at reducing greenhouse gas emissions and enhancing energy security, biofuels have sparked debate within the scientific community. Critics highlight potential risks to global food security and question whether biofuels consistently deliver the expected environmental benefits (Borras et al., 2010).

This study contributes to the existing literature by providing a comprehensive techno-economic assessment of biofuel utilization and waste-to-energy systems, while examining their role in supporting the sustainable energy transition and circular economy strategies. In addition, it incorporates multiple case studies from different geographical contexts to highlight practical challenges, economic feasibility, and policy implications associated with the deployment of bioenergy technologies. Despite the extensive literature on biofuels and renewable energy systems, limited studies provide an integrated techno-economic assessment that simultaneously examines biofuel production, waste-to-energy systems, and their implications for sustainable energy transition. In addition, comparative insights from different geographical contexts remain relatively limited in the existing literature. Therefore, this study aims to provide a comprehensive techno-economic evaluation of biofuel utilization and waste-to-energy systems, supported by case studies from different regions. The analysis highlights the technological, economic, environmental, and policy dimensions associated with the deployment of bioenergy technologies.

# 2. TYPES OF BIOFUELS

The term “biofuels” encompasses a wide range of energy carriers derived from biological sources, including biodiesel, bioethanol, biogas, biomethanol, bio-dimethyl ether, biohydrogen, bio-ETBE, bio-MTBE, synthetic biofuels, and pure vegetable oils (Dounavis et al., 2015; Dounavis et al., 2016). In this study, a detailed assessment focuses specifically on biodiesel, bioethanol, biomethanol, biogas, and biohydrogen (Dounavis & Tasionas, 2019; Dounavis et al., 2019a; Dounavis et al., 2019b).

Biofuels are commonly grouped into four generations:

- **First-generation biofuels**, often called conventional biofuels, are produced using well-established technologies and processes, primarily relying on food-based feedstocks such as sugarcane, corn, and vegetable oils.
- **Second-generation biofuels** are derived from non-food biomass through thermochemical and catalytic processes such as pyrolysis, gasification, and Fischer–Tropsch synthesis. Their main advantage over first-generation fuels lies in avoiding the competition between food and fuel, utilizing agricultural residues, lignocellulosic biomass, and other non-edible sources (Barbera et al., 2022).
- **Third-generation biofuels** primarily employ microalgae as feedstock. Although initially classified under second-generation biofuels, extensive research has revealed that microalgae can achieve significantly higher yields with lower resource inputs, making them a distinct and promising category in biofuel development (Neto et al., 2019).
- **Fourth-generation biofuels** are designed to integrate biofuel production with active carbon capture and storage (CCS). This group includes fuels such as biohydrogen, biomethane, and various synthetic biofuels. Unlike previous generations, fourth-generation biofuels can capture $CO_2$ during production, which is then sequestered—typically in depleted gas fields or salt caverns—thus contributing to a net reduction in atmospheric carbon levels (Goria et al., 2022).

### 2.2.1 BIODIESEL

#### 2.2.1.1 Brief Historical Overview of Biodiesel

Biodiesel traces its origins back over a century to 1892, when Rudolf Diesel designed an engine capable of operating on a variety of fuels, including vegetable oils. This marked the earliest recorded use of vegetable oils as an alternative energy source. Notably, in 1900, a diesel engine exhibited at the Paris Exhibition was fueled with peanut oil. Despite these early demonstrations, the widespread availability and low cost of petroleum at the time limited interest in alternative fuels (Pahl, 2005; Gebremariam & Marchetti, 2017).

By the 1930s, research began focusing on separating fatty acids from glycerin to produce a thinner oil resembling conventional diesel. In 1937, Chavanne obtained a Belgian patent for an ethyl ester derived from palm oil, now recognized as biodiesel (Al Seadi, 2008; Bernard & Rémond, 2012; Atabani et al., 2012; Atadashi et al., 2013).

During World War II (1939–1945), when petroleum supplies were scarce, countries such as Brazil, Argentina, China, India, and Japan turned to vegetable oils as fuel. After the war, as petroleum once again became abundant and inexpensive, the use of vegetable oil as fuel declined (Bušić et al., 2018).

The oil embargo of the 1970s rekindled interest in vegetable oils as an energy source. Research in countries including Austria, the United States, and South Africa revealed that pure vegetable oil could operate diesel

engines, though high viscosity led to poor atomization and potential engine damage. Thus, efforts began to chemically convert vegetable oils into biodiesel, a term likely first coined around 1984 (Luque et al., 2008; Ma & Hanna, 1999; Mao et al., 2015; Marchetti et al., 2007; Marchetti et al., 2008).

In 1985, the first biodiesel production facility became operational at an agricultural school in Austria. Production expanded across Europe in the early 1990s, notably in the Czech Republic, Sweden, and Germany, the latter becoming a leading producer. In the United States, commercial biodiesel production started in 1991 in Kansas City, Missouri, and in 1995 the University of Idaho supplied biodiesel to Yellowstone National Park, demonstrating its safe and long-term use in vehicles. Following this success, other national parks adopted biodiesel (Pahl, 2005).

Globally, biodiesel production also developed on other continents, utilizing palm oil in Malaysia and soybean oil in South America. By the late 1990s, environmental concerns accelerated the production of methyl esters, and the Austrian Biofuels Institute reported that 21 countries were actively trading biodiesel by the decade's end (Kaifa & Parawira, 2019; Kalam & Masjuki, 2002; Neto et al., 2019).

Today, biodiesel can be used either neat or blended with conventional diesel. Low-percentage blends are compatible with nearly all diesel engines and existing storage and distribution systems, while higher-percentage blends can be employed in modern engines with minimal or no modifications (Portillo et al., 2015; Hasan & Rahman, 2017; IRENA, 2018; Jingura & Matengaifa, 2009).

2.2.1.2 Main Characteristics of Biodiesel

Biodiesel, like all biofuels, serves as an alternative to conventional diesel fuel. Its quality is assessed based on physicochemical properties, which must be environmentally sustainable and compatible with engine performance, avoiding operational issues (Portillo et al., 2015; Ma & Hanna, 1999; O'Connor et al., 2020; Parawira, 2010).

Biodiesel is typically a liquid fuel, often referred to as B100, with characteristics strongly influenced by the feedstock employed during production. Its performance under low-temperature conditions depends on the blend ratio, the type of feedstock, and the properties of the conventional diesel it is mixed with. Generally, blends containing lower percentages of biodiesel exhibit better cold-weather behavior; for instance, standard No. 2 diesel and B5 blends (up to 5% biodiesel) perform comparably in freezing temperatures. Both biodiesel and No. 2 diesel include compounds prone to crystallization at very low temperatures.

To mitigate cold-flow issues during winter, fuel suppliers commonly incorporate cold-flow additives. For optimal performance in colder climates, end-users are advised to coordinate with suppliers to ensure that the selected biodiesel blend meets operational requirements (Kajau et al., 2019; Kalam & Masjuki, 2002).

2.2.1.3 Quality of Biodiesel

This subsection examines the key parameters that influence and determine the overall quality of biodiesel. According to the literature, several factors contribute to the physicochemical characteristics of biodiesel fuel, with four primary elements playing a decisive role (Park, 2010).

• *Feedstock Origin*

The origin of the feedstock represents one of the most important factors affecting biodiesel quality. It refers to the raw materials used for fuel production, whose chemical composition and physical properties significantly

influence the final characteristics of the produced biodiesel. Several aspects related to feedstock selection should be considered:

1. *Oil Content* : Oilseed crops such as sunflower, rapeseed, and jatropha contain high concentrations of oil in their seeds. These feedstocks are typically assessed based on their oil yield per hectare as well as their cultivation and harvesting cycles, which directly affect biodiesel productivity.
2. *Fatty Acid Profile*: The fatty acid composition of the raw material plays a crucial role in determining biodiesel properties. A high concentration of certain fatty acids may influence fuel stability and alter important physicochemical characteristics.
3. *Oxidative Stability*: Oxidative stability refers to the resistance of oils to chemical or physical degradation over time. Since vegetable oils are susceptible to reactions with oxygen and other environmental factors, their stability during storage can be influenced by the structure of fatty acid esters, including chain length and degree of saturation.
4. *Temperature Sensitivity*: Temperature is another important parameter affecting biodiesel quality. Due to the presence of unsaturated fatty compounds, biodiesel often exhibits lower oxidative stability compared with petroleum diesel. Nevertheless, biodiesel derived from feedstocks such as soybean, sunflower, peanut, and cottonseed oils generally demonstrates improved cold-flow properties and greater stability under low-temperature conditions (World Biogas Association, 2016; Williams et al., 2016).

• *Production Process*

The production method is also a critical determinant of biodiesel quality. Parameters such as water content and the presence of impurities, including residual catalysts, must be carefully controlled during processing. In order to meet established fuel standards, several purification stages are required, including the removal of catalyst residues, excess alcohol, and glycerol. Ultimately, biodiesel must comply with defined physicochemical specifications before it can be approved for commercial or industrial use.

• *Biodiesel Distribution and Storage*

Distribution and storage conditions are closely related and have a significant impact on biodiesel stability. Biodiesel typically exhibits a flash point of approximately 127°C, which is considerably higher than that of conventional diesel (around 52°C), making it safer for handling and transportation. However, because biodiesel originates from biological feedstocks, microbial growth such as bacteria and mold may occur during storage. For this reason, regular monitoring of water content is necessary. In addition, biodiesel should ideally not be stored for periods exceeding six months unless stabilizing additives, such as antioxidants, are applied to preserve fuel quality. Maintaining biodiesel quality is particularly important in maritime applications, where fuel stability and storage conditions directly affect engine efficiency and operational reliability.

2.2.2 BIOGAS

2.2.2.1 Brief Historical Overview of Biogas

Historical evidence suggests that biogas has been utilized for centuries. According to the World Biogas Association (2016), as early as 900 B.C., biogas was reportedly used in Assyria for heating bathwater. The scientific understanding of methane, however, emerged much later and is commonly attributed to the Italian physicist Alessandro Volta, who in the late 18th century investigated the production of flammable gases from decomposing organic matter. His work was partly inspired by earlier discussions on “flammable air,” including

writings by Benjamin Franklin. Subsequent research confirmed that methane is naturally generated in marshes and wetlands during the anaerobic decomposition of organic materials. This discovery eventually led to the construction of the first known biogas digester in 1859 in Bombay (Mumbai), India. Around the same period, sewer gas was captured and utilized for street lighting in Victorian England (Chaturvedi et al., 2012; Chisti & Karimi, 2022; Cucchiella et al., 2019).

The development of modern biogas technology accelerated during the early 20th century. In the 1930s, biogas plants were increasingly associated with municipal wastewater treatment systems, where anaerobic digestion was used to stabilize sludge while simultaneously producing energy. Throughout the century, growing concerns regarding waste management and energy supply stimulated further technological progress, with notable developments occurring in countries such as China, Germany, and the United States (IRENA, 2018).

In the 21st century, the expansion of biogas production has been strongly supported by policy measures promoting renewable energy, including feed-in tariff (FIT) schemes and other incentives for clean fuel generation. These initiatives have encouraged the deployment of both small-scale and industrial-scale anaerobic digestion facilities across many regions of the world.

Today, the efficiency and reliability of biogas systems continue to improve due to advances in engineering design, materials science, automation technologies, and biological process optimization. Nevertheless, the increasing technological sophistication of modern biogas plants also results in greater operational complexity and higher investment costs. Accordingly, the successful operation of contemporary biogas facilities requires careful system design, continuous monitoring, and effective management of the entire production chain (Bertrand & Dussap, 2022). As a result, biogas has emerged as an important renewable energy carrier that simultaneously contributes to waste management, energy diversification, and greenhouse gas mitigation.

2.2.2.2 Main Characteristics of Biogas

In recent decades, the global transition toward sustainable development has intensified efforts to address environmental challenges largely associated with extensive fossil fuel consumption. The continuous growth in energy demand, combined with concerns regarding resource depletion and environmental impacts, has prompted researchers and policymakers to explore alternative renewable energy sources, including various forms of biofuels (IEA Bioenergy, 2022; Inter-American Development Bank, 2014; IRENA, 2018; Jingura & Matengaifa, 2009; Kaifa & Parawira, 2019).

Among these alternatives, biogas represents an important renewable fuel that can be produced through the biological process of anaerobic digestion. During this process, microorganisms break down organic matter in oxygen-free conditions, generating a gaseous mixture primarily composed of methane and carbon dioxide. Anaerobic digestion occurs naturally in environments such as wetlands, swamps, landfills, and in the digestive systems of ruminant animals (Scarlat et al., 2018).

Biogas can be captured and utilized as a reliable energy source through relatively simple technological systems. In addition to energy production, the anaerobic digestion process may also generate valuable by-products with industrial or agricultural applications. The increasing interest in biogas technology is therefore associated both with its potential as a renewable energy carrier and with the need to control methane emissions, which contribute significantly to greenhouse gas accumulation in the atmosphere.

Typically, biogas is produced from plant-based biomass and organic waste streams, including agricultural residues, household organic waste, industrial by-products, and dedicated energy crops (Divya et al., 2015). Modern biogas facilities convert these materials into methane-rich gas that can be used for electricity generation, heat production, or further upgraded to biomethane.

Once purified, upgraded biogas may be compressed and injected into existing natural gas networks or utilized as a fuel in internal combustion engines and transport systems. One of the main advantages of biogas technology lies in its ability to convert complex organic materials, particularly polysaccharides contained in plant biomass, into useful energy within relatively small and decentralized industrial units.

An additional environmental benefit of anaerobic digestion is the recycling of nutrients and organic matter. The digestate produced during the process contains valuable minerals, phosphates, and fibrous materials that can be returned to agricultural soils as fertilizers or soil conditioners, thereby contributing to circular resource management and improved soil fertility.

Although biogas technology has reached a relatively advanced level of development, there remains significant potential for further optimization. Ongoing research focuses on improving reactor design, process control, and the integrated utilization of by-products, which may lead to the development of large-scale and technologically advanced production facilities in the future (Acien et al., 2017; Agarwal, 2007; De Cagalitan & Abundo, 2021). For this reason, biogas technology is increasingly considered a key component of integrated waste management and renewable energy systems.

2.2.2.3 Quality of Biogas

The quality of biogas is closely related to both the characteristics of the feedstock and the conditions under which anaerobic digestion takes place. Before examining the quality parameters of biogas, it is useful to briefly outline the basic principles of the anaerobic digestion process used in biogas plants.

Anaerobic digestion is a biological process in which microorganisms decompose organic matter in the absence of oxygen. This process naturally occurs in environments such as manure storage systems, wetlands, and landfills, where large quantities of organic material and limited oxygen availability create favorable conditions for anaerobic microbial activity. When this process occurs in an uncontrolled manner, it may generate unpleasant odors commonly associated with the storage and spreading of manure. However, when anaerobic digestion is properly managed in biogas facilities, these emissions can be significantly reduced while simultaneously producing usable energy in the form of biogas.

During controlled anaerobic digestion, organic substrates such as manure and other biodegradable materials are converted into biogas and a nutrient-rich residual product known as digestate. This digestate generally has lower odor intensity, improved biological stability, and a reduced tendency for further decomposition compared to the original feedstock.

The biogas production process typically involves three main biological stages. In the first stage, known as liquefaction or hydrolysis, specialized bacteria break down complex insoluble organic compounds—including carbohydrates, fats, and proteins—into smaller soluble molecules. Some fibrous materials may remain undegraded and either accumulate within the digester or exit the system as part of the residual digestate.

In the second stage, acidogenic bacteria convert these soluble compounds into intermediate products, primarily volatile fatty acids. These organic acids are responsible for many of the odors associated with untreated organic waste.

Finally, in the third stage, methanogenic microorganisms convert volatile fatty acids and other intermediate compounds into biogas. The resulting gas mixture typically contains approximately 60% methane ($CH_4$) and 40% carbon dioxide ($CO_2$), along with smaller quantities of water vapor, hydrogen sulfide ($H_2S$), ammonia, and other trace gases.

For biogas to be suitable for practical energy applications, purification is often required in order to remove undesirable components such as sulfur compounds and halides. The acceptable concentrations of these substances are usually determined by equipment manufacturers and, in certain cases, by national regulatory standards. These requirements may vary between countries. For instance, German regulations limit hydrogen sulfide concentrations in combustible gases to approximately 5 mg/m³, whereas Polish and Hungarian standards allow concentrations of up to 20 mg/m³ (Zamorska-Wojdyła et al., 2012).

In applications involving gas engines, boilers, or combined heat and power systems, equipment manufacturers may specify different tolerance limits for hydrogen sulfide and total sulfur content. For example, certain generator systems recommend that hydrogen sulfide concentrations should not exceed 200 mg/m³ prior to gas purification stages, while total sulfur levels at the engine inlet may be restricted depending on the presence of catalytic converters.

Additional quality parameters of biogas are also influenced by operational characteristics of the digestion process. Important factors include water content, operating temperature, hydraulic retention time, and microbial activity within the digester.

The water content of the digestion mixture may vary widely depending on the type of feedstock used. Lower water content may complicate pumping and mixing operations, whereas higher water content increases the heat demand required to maintain stable reactor temperatures.

Operating temperature is another critical parameter affecting microbial activity and process efficiency. Anaerobic digesters typically operate within psychrophilic (10–20°C), mesophilic (30–40°C), or thermophilic (50–60°C) temperature ranges. Higher temperatures generally accelerate reaction rates and improve methane production, although they also require greater energy input for system heating.

Hydraulic retention time, which represents the average time that the substrate remains in the digester, may range from a few days to several weeks depending on reactor design and operating conditions. Finally, the efficiency of methane production is strongly influenced by the composition and stability of the microbial community involved in the digestion process. Since the biological mechanisms governing these microbial interactions remain an active area of research, further advances in biotechnology and process optimization are expected to improve the efficiency of future biogas systems (Bertrand & Dussap, 2022). Therefore, ensuring high biogas quality is essential for maximizing energy efficiency, protecting energy conversion equipment, and ensuring the reliable operation of biogas-based energy systems.

2.2.3 BIOETHANOL

2.2.3.1 Brief Historical Overview of Bioethanol

Bioethanol ($C_2H_5OH$), or ethyl alcohol, is a widely used biofuel primarily employed as a gasoline additive. Engines capable of running on pure ethanol or high-ethanol blends are increasingly available and utilized globally (Chisti & Karimi, 2022). The origins of ethanol production trace back centuries to traditional fermentation practices for alcoholic beverages. However, its use as a fuel emerged in the late 19th and early 20th centuries with the advent of internal combustion engines, as early experiments by Nikolaus Otto demonstrated ethanol's feasibility as a fuel source (Luque et al., 2008).

During the Prohibition era in the United States, ethanol gained attention as a gasoline substitute, highlighting its flexibility. Later, the environmental movement and rising concerns about fossil fuel depletion brought bioethanol to the forefront as a renewable energy alternative. Governments worldwide introduced incentives for bioethanol production and blending with gasoline to reduce greenhouse gas emissions and improve energy security. Advances in biotechnology and agriculture further accelerated its commercial adoption.

Despite challenges related to food prices, land-use competition, and energy balance, bioethanol continues to play a significant role in renewable energy strategies. By 2016, global bioethanol production reached 18.3 million tons, with Europe contributing approximately 310,000 tons, representing 17.8% of total European biofuel production.

2.2.3.2 Main Characteristics of Bioethanol

Bioethanol is widely used in blends ranging from 10% to 85%, with the United States being the largest producer and Brazil the largest exporter, together accounting for about 70% of global bioethanol production. Flex-fuel vehicles (FFVs) in countries such as Sweden, the United States, and Brazil operate on high-ethanol blends like E85 (85% ethanol, 15% gasoline) or pure ethanol (E100) in adapted engines (Luque et al., 2008).

Production of bioethanol involves several key steps:

- Preparation of raw materials: Plant-based feedstocks, such as corn, sugarcane, or wheat, are processed to extract fermentable sugars.
- Fermentation: Microorganisms, mainly yeasts, convert sugars into ethanol and by-products.
- Separation: Ethanol is separated from residual solids through filtration or other separation techniques.
- Distillation: The ethanol-water mixture is distilled to increase ethanol concentration, often using fractional or head-heart-tail distillation.
- Purification and final processing: The product is refined to meet quality specifications and regulatory standards.

2.2.3.3 Bioethanol Quality

The quality of bioethanol is critical for its safe and efficient application in transport fuels, industrial processes, chemical synthesis, and pharmaceuticals. High-grade bioethanol typically exceeds 99% purity, minimizing the presence of water, acids, aldehydes, and other contaminants. Maintaining water content below 1% is essential to preserve fuel integrity and engine performance.

Physical characteristics such as colorlessness and odor serve as indicators of purity, while deviations may signal contamination or decomposition, requiring additional quality control. Regulatory compliance is vital, with bioethanol subject to strict standards established by national and international authorities. Certifications from

recognized organizations provide assurance of conformity and consumer confidence (European Commission, 2008).

Storage stability is another key factor; bioethanol must retain its quality during storage and transport, necessitating proper handling practices. Overall, maintaining high-quality bioethanol supports its sustainable and efficient use, fostering innovation and progress toward a low-carbon energy future (Bertrand & Dussap, 2022).

### 2.2.4 BIOMETHANE

#### 2.2.4.1 Brief Historical Overview of Biomethane

Biomethane is a renewable gaseous fuel obtained through the upgrading and purification of biogas. Since biogas itself is produced through anaerobic digestion of organic matter, the fundamental processes leading to biomethane formation have existed for thousands of years in natural environments. However, the concept of biomethane as a renewable substitute for conventional natural gas gained significant attention only in recent decades.

The development of biomethane technology accelerated during the late 20th and early 21st centuries, driven by increasing interest in renewable energy systems and sustainable waste management. Advances in upgrading technologies have made it possible to purify raw biogas by removing carbon dioxide, hydrogen sulfide, moisture, and other impurities, thereby producing biomethane with a composition comparable to natural gas (IEA Bioenergy, 2022).

Biomethane can be produced from a wide range of organic feedstocks, including agricultural residues, animal manure, sewage sludge, municipal organic waste, and food-processing by-products. Over the past few decades, technological improvements in biogas upgrading, gas purification, and energy integration have significantly enhanced the efficiency and economic viability of biomethane production systems.

A major milestone in the development of biomethane technology was the establishment of the first large-scale biomethane upgrading facilities in the early 2000s. These plants demonstrated that biomethane could be produced at industrial scale and injected into natural gas grids or used as a renewable transport fuel.

Today, biomethane is increasingly recognized as a versatile renewable energy carrier that contributes to both sustainable waste management and the decarbonization of the energy sector. Ongoing technological innovations and supportive energy policies are expected to further expand the role of biomethane in future low-carbon energy systems (IEA Bioenergy, 2022). Consequently, biomethane is increasingly viewed as a strategic renewable fuel capable of supporting energy transition and circular economy initiatives.

#### 2.2.4.2 Main Characteristics of Biomethane

Biomethane exhibits physicochemical properties that are very similar to those of conventional natural gas, primarily because methane ($CH_4$) is its dominant component. As a result, biomethane can be utilized within existing natural gas infrastructure, including pipelines, storage systems, and gas distribution networks (IEA Bioenergy, 2022; Hansen et al., 2007).

Due to this similarity, biomethane can be injected into natural gas grids or used as a fuel for electricity generation, heating applications, and transportation systems without requiring significant modifications to existing technologies. The main physicochemical characteristics of biomethane are presented in Table 1.

Table 1
Main physicochemical characteristics of biomethane(Hansen et al., 2007)

| Characteristics | Values |
|---|---|
| Molecular weight | 16.04 g/mol |
| Density (at 0°C) | 0.717 kg/m³ |
| Density (at 20°C) | 0.655 kg/m³ |
| Boiling point | -161.5°C |
| Melting point | -182.5°C |
| Flammability | Flammable |
| Odor | Odorless |
| Color | Colorless |
| Solubility in water | Low |

The physical properties of biomethane make it suitable for a wide range of energy applications. In its pure form, biomethane is a colorless and odorless gas with high flammability and relatively low density. Due to its low solubility in water and favorable combustion properties, it can be efficiently used in gas engines, combined heat and power (CHP) systems, and transport fuels.

Because of these characteristics, biomethane is increasingly considered a promising renewable alternative to fossil natural gas, particularly in energy systems aiming to reduce greenhouse gas emissions and improve sustainability.

2.2.4.3 Biomethane Quality

The quality of biomethane is determined by several parameters that influence its composition, energy content, and suitability for various energy applications. One of the most important indicators of biomethane quality is the methane concentration, which typically ranges between 90% and 99%. Higher methane content corresponds to greater calorific value and improved fuel performance, making the gas more comparable to conventional natural gas (SRA, n.d.).

Another important factor affecting biomethane quality is the presence of impurities, including carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), water vapor ($H_2O$), and trace contaminants. These components must be removed or reduced to acceptable levels in order to ensure safe and efficient use of the gas. For example, elevated concentrations of carbon dioxide reduce the overall energy content of the fuel, while hydrogen sulfide can cause corrosion in pipelines, storage systems, and energy conversion equipment if not adequately treated (SRA, n.d.).

To achieve the required quality standards, raw biogas must undergo upgrading and purification processes that remove undesirable components and increase methane concentration. Common upgrading techniques include gas compression, dehydration, and gas cleaning technologies such as chemical absorption, pressure swing

adsorption, and membrane separation. In addition, odorizing agents are often added to biomethane before distribution in order to facilitate leak detection and improve operational safety (SRA, n.d.).

Quality requirements for biomethane may vary depending on its final application. In particular, biomethane intended for injection into natural gas grids must comply with strict specifications regarding methane concentration, moisture content, and allowable levels of contaminants. Similarly, biomethane used as a transport fuel or for electricity and heat generation must satisfy specific regulatory and technical standards established by national authorities and energy regulators.

Ensuring high biomethane quality is therefore essential for its efficient utilization and for its safe integration into existing natural gas infrastructures. By meeting established quality standards and minimizing impurities, biomethane can serve as a reliable renewable energy carrier contributing to greenhouse gas emission reduction, improved energy security, and the transition toward more sustainable energy systems (SRA, n.d.). Therefore, maintaining high biomethane quality is essential for ensuring its safe integration into natural gas infrastructures and for maximizing its contribution to low-carbon energy systems.

### 2.2.5 BIOHYDROGEN

#### 2.2.5.1 Brief Historical Overview of Biohydrogen

Hydrogen was first identified in 1766 by the English scientist Henry Cavendish, who isolated the gas through the reaction of zinc with hydrochloric acid. During experiments presented at the Royal Society of London, Cavendish demonstrated that hydrogen reacts with oxygen to produce water, contributing to the early understanding of the chemical composition of water (Dounavis et al., 2015). These discoveries laid the scientific foundation for later research into hydrogen as a potential energy carrier.

Throughout the 18th and 19th centuries, several scientists investigated the properties and potential applications of hydrogen. Significant progress in understanding biological hydrogen production emerged in the early 20th century. In 1933, Marjory Stephenson and her student Leslie T. Stickland reported that certain microbial cell suspensions could catalyze the reduction of methylene blue using molecular hydrogen. Their work provided early insights into microbial hydrogen metabolism (Dounavis et al., 2016).

Further advances occurred in 1939 when Hans Gaffron observed that the green microalga Chlamydomonas reinhardtii was capable of producing hydrogen under specific environmental conditions. This discovery represented one of the first demonstrations of biological hydrogen production through photosynthetic organisms.

Later research significantly advanced the understanding of algal hydrogen production. The Greek scientist Anastasios Melis demonstrated that sulfur deprivation can trigger a metabolic shift in algae from oxygen-producing photosynthesis to hydrogen production (Melis & Happe, 2001). In this process, the enzyme hydrogenase plays a key role, although its activity is inhibited in the presence of oxygen. Melis showed that limiting sulfur availability disrupts internal oxygen evolution within the algal cells, thereby creating conditions that allow hydrogenase to function and enabling biological hydrogen generation (Acien et al., 2017; Agarwal, 2007).

These discoveries laid the groundwork for modern research into biohydrogen production technologies, which are increasingly explored as part of future sustainable and low-carbon energy systems (Gu et al., 2020). As a

result, biohydrogen has attracted growing scientific interest as a clean energy carrier with significant potential for future renewable energy systems.

2.2.5.2 Main Characteristics of Biohydrogen

Biohydrogen is a carbon-free renewable energy carrier that can be produced from the fermentation of organic substrates, including sugars derived from biomass and liquid waste. It is recognized as a highly efficient energy vector, as its utilization in fuel cells or combustion processes generates water as the sole by-product, alongside significant energy output.

Several methods exist for biohydrogen production, including biophotolysis of water, dark fermentation, photofermentation, and microbial electrolysis cells. These technologies primarily rely on organic waste materials and water, providing the additional advantage of avoiding competition with food resources and contributing to circular economy objectives.

Biohydrogen has particularly promising applications in fuel cells, where it can be directly converted into electricity without combustion, producing only water and heat. This feature makes it an attractive option for low-emission power generation across multiple sectors. Nonetheless, challenges remain in the large-scale deployment of biohydrogen, including the need for optimization of operational parameters, purification and conditioning prior to end-use, and improvements in storage and transport efficiency (Czernik & Bridgewater, 2004; Garcia, 2014; Goria et al., 2022).

Maintaining high biohydrogen quality is essential to maximize energy efficiency, ensure compatibility with fuel cell technologies, and support the integration of hydrogen into sustainable energy systems. Overall, high-quality biohydrogen production can support the decarbonization of energy systems, contribute to a circular economy by valorizing waste streams, and play a strategic role in future sustainable energy policies.

2.2.5.3 Biohydrogen Quality

The quality of biohydrogen is a critical factor that directly affects its performance, safety, and environmental benefits. To ensure optimal utilization, biohydrogen must exhibit high purity, minimal moisture content, and be free from impurities such as carbon monoxide (CO), methane ($CH_4$), and hydrogen sulfide ($H_2S$).

High purity is essential for maximizing energy output in fuel cells or combustion applications, while excessive moisture can lead to storage complications and corrosion within distribution systems. Likewise, the presence of impurities can compromise operational efficiency, reduce energy yields, and pose safety risks, highlighting the importance of effective purification and conditioning processes.

Compatibility with existing gas infrastructure and the absence of toxic by-products are additional critical requirements for the large-scale adoption of biohydrogen. Maintaining these quality standards is essential for realizing biohydrogen's full potential as a clean, renewable energy source and for facilitating its integration into diverse energy systems and industrial applications (Hasan & Rahman, 2017; IEA Bioenergy, 2022; IRENA, 2018; Jingura & Matengaifa, 2009). From this perspective, maintaining high-quality biohydrogen is crucial not only for technical performance but also for supporting decarbonization strategies, promoting circular economy practices by valorizing organic waste, and enabling its adoption across diverse energy and industrial sectors.

# 3. BIOFUEL PRODUCTION PROCESSES

Biofuels, particularly biodiesel, are commonly produced from vegetable and animal oils, which require pre-treatment due to high viscosity and other inherent limitations (Jingura & Matengaifa, 2009).

## 3.1. Alkylation Method (Transesterification)

The alkylation method, also known as transesterification, is the most widely employed approach worldwide. Transesterification involves the reaction of a triglyceride (triester of glycerol with fatty acids) with an alcohol to yield a new ester and a new alcohol, whereas esterification refers to the reaction of free fatty acids with alcohol to produce esters and water. Vegetable and animal oils primarily contain triglycerides (up to 98% w/w), along with diglycerides, monoglycerides, free fatty acids, and minor constituents such as phosphatides, carotenoids, tocopherols, and water. The composition of fatty acids varies in carbon chain length and degree of unsaturation (O'Connor et al., 2020; Bernard & Rémond, 2012; Odejobi et al., 2023).

Several techniques are employed to facilitate transesterification, including:

- Acid homogeneous transesterification
- Alkaline homogeneous catalytic transesterification
- Heterogeneous catalytic transesterification
- Enzymatic catalytic transesterification
- Nano-catalysis
- Transesterification using ionic liquids as catalysts
- Supercritical transesterification

Proper selection of the transesterification method and optimization of reaction parameters are essential to achieve high biodiesel yield, ensure fuel quality, and meet regulatory standards.

## 3.2 Pyrolysis

Pyrolysis constitutes a thermochemical method for converting biomass into multiple products, including bio-oil, non-condensable gases, and solid char. This process is conducted in an oxygen-free environment, typically at temperatures ranging from 450 to 500°C, often in fluidized bed reactors with recirculation. The distribution of products—gaseous, liquid, or solid—depends strongly on the heating rate and the residence time of the biomass in the reactor. Variants of pyrolysis include in Table 2:

Table 2
Categories of Pyrolysis

| Method | Temperature (°C) | Residence Time | Heating Rate (°C/s) | Major Products |
|---|---|---|---|---|
| Conventional / Slow Pyrolysis | Medium–high (400–500) | Long, 5–30 min | Low (~ 10) | Gases, Char, Bio-oil (tar) |
| Fast Pyrolysis | Medium–high (400–650) | Short, 0.5–2 s | High (~ 100) | Bio-oil (thinner), Gases, Char |
| Ultra-fast / Flash Pyrolysis | High (700–1000) | Very short, < 0.5 s | Low (~ 10) | Gases, Bio-oil |

Optimizing operational parameters is crucial to maximize the yield of desired products and ensure that bio-oil and biogas fractions meet quality requirements for energy applications (Bernard & Rémond, 2012; Diaz et al., 2014).

## 3.3 Dilution with Conventional Diesel

A practical approach for overcoming the high viscosity of vegetable or animal oils is blending them with conventional diesel fuel. This method reduces viscosity, facilitates smoother fuel injection, and minimizes carbon deposition within engines. The process does not involve complex chemical reactions, but careful control of fuel ratios and temperatures is required to maintain performance and meet regulatory standards. Despite these benefits, the incorporation of fossil diesel limits the renewable fraction of the resulting fuel, reducing its potential contribution to decarbonization and sustainable energy strategies (Uddin & Wright, 2023; Verma et al., 2019; Wang et al., 2023).

## 3.4 Microemulsion

Microemulsion production is a chemical approach that generates a stable, isotropic mixture of oil, water, and surfactant, typically with droplet sizes ranging from 1 to 100 nm. In the context of biofuels, microemulsions can be created using vegetable oils, alcohols, surfactants, and cetane improvers, with or without the addition of diesel. Short-chain alcohols such as butanol, hexanol, or octanol are commonly used to reduce viscosity and improve combustion characteristics. Microemulsions can achieve performance comparable to conventional diesel, offering a viable solution for high-viscosity feedstocks while maintaining a renewable content suitable for energy transition objectives (Piadeh et al., 2024).

# 4. TECNO-ECONOMIC STUDIES

## 4.1 Biogas Unit in the City of El Alto, Bolivia

This study was selected from scientific databases due to its comprehensive techno-economic analysis of a small-scale biogas facility for organic waste treatment in El Alto, Bolivia, highlighting both environmental and social benefits (Garcia, 2014; Inter-American Development Bank, 2014). Waste management in El Alto is regulated by the municipal government, which collaborates with private concession companies responsible for waste collection, transportation, and disposal. The primary landfill, Villa Ingenio, was projected to reach full

capacity by 2015, prompting the exploration of alternative waste treatment technologies (Garcia, 2014; Riaño et al., 2023).

Approximately 67% of the city's waste consists of organic material suitable for anaerobic digestion. While prior studies in Bolivia primarily examined large-scale treatment of animal manure and municipal organic fractions, this investigation focused on the potential of a small-scale biogas unit processing organic waste from the city's fruit and vegetable markets. The analysis assumed an annual availability of 10,000 tons of biodegradable waste (Ajdari, 2021).

A multi-criteria analysis (MCA) was conducted to identify the most appropriate technology for local conditions, considering four digester designs: tubular, Chinese dome, Indian floating drum, and garage-shaped digesters. Evaluation criteria included lifespan, required technical expertise, structural characteristics, and investment cost. The analysis concluded that the garage-shaped digester was the optimal choice. Based on its characteristics, the potential biogas production was estimated at 1,000,000 $Nm^3$ per year, corresponding to approximately 1.8 GWh of electricity annually. The digested residue could yield around 2,340 tons of organic fertilizer per year, suitable for commercialization.

The economic assessment employed NPV (Net Present Value), IRR (Internal Rate of Return), payback period, and LCOE (Levelized Cost of Energy), based on a biogas unit with 250 kWel capacity. Two operational scenarios were considered: (I) operation solely for waste treatment, and (II) operation covering waste collection, transport, and treatment. Both scenarios were evaluated with and without carbon credits. Scenario II with carbon credits proved most attractive; nevertheless, both scenarios exhibited positive NPV, IRR exceeding the 5% discount rate, and payback periods of approximately five years, demonstrating economic viability. The electricity and organic fertilizer prices were taken as $0.09/kWh and $140/ton, respectively, in 2014.

LCOE values were calculated at $0.17/kWh for Scenario I and $0.26/kWh for Scenario II, significantly above the subsidized natural gas rate of $0.026/kWh in Bolivia. As a result, financial incentives such as investment subsidies or feed-in tariffs are necessary to render electricity from biogas competitive. Sensitivity analysis, varying parameters by ± 50%, identified the price of compost as the most influential factor, while all variations maintained positive NPV, indicating profitability under uncertain conditions.

The study further examined the market potential for by-products. Electricity could be sold if supported by government mechanisms, and organic fertilizer could replace imports, provided adequate promotion and regulatory support. Environmental benefits were also quantified: approximately 900 tons of $CO_2$ emissions could be avoided annually, contributing to climate change mitigation. Social benefits include reduced dependence on fossil fuels, increased utilization of renewable energy, and a 6% reduction in landfill waste.

In summary, a small-scale biogas facility in El Alto could simultaneously generate green electricity and organic fertilizers, achieve cost recovery, and deliver environmental and social advantages. Governmental support through subsidies, awareness programs, and economic incentives is critical to enable successful implementation and market integration.

## 4.2 Case Study of a Biogas Unit in Northern Italy

This case study examines a biogas facility located in Northern Italy. The system was simulated using Aspen Plus v.11, based on a feed stream of 1 ton/day of OFMSW (Organic Fraction of Municipal Solid Waste),

representing an equivalent population of 2,000–2,500 people. The ELECNRTL (electrolyte non-random two-liquid) model was used to capture chemical equilibria of ionic species, while the Peng-Robinson equation of state was applied to model the biogas co-generation process in the combined heat and power (CHP) unit (Singh & Kalamdhad, 2023; Sisto et al., 2017). The process flow was divided into three main sections: anaerobic digestion (AD), CHP co-generation, and algae cultivation, described in detail below.

- Anaerobic Digestion (AD)

The AD section was modeled to replicate the operational parameters of a micro-digestion facility processing OFMSW, located in Arzignano, Vicenza (Italy). The system is designed for 1 ton/day of OFMSW, with a total solids (TS) content of 25%, corresponding to 75% moisture. Seasonal variations result in feed temperatures between 5–25°C. Before entering the digester, the feed is combined with a fraction of recycled liquid digestate (stream LIQ-REC), which preheats the feed and reduces the TS content to 12%, simulating a wet digestion system. The slurry is subsequently heated to the digestion temperature of 37°C.

This simulation assesses the technical and economic feasibility of the unit under the local conditions of Northern Italy, taking into account the characteristics of regional organic waste (Singh & Kalamdhad, 2023; Sisto et al., 2017). The study evaluates potential biogas production, plant efficiency, electricity and heat output, and the associated economic returns. The model incorporates the unique properties of OFMSW, addressing operational challenges in processing this type of feedstock.

- Combined Heat and Power (CHP) and Algae Cultivation

The integration of anaerobic digestion with CHP allows for simultaneous production of electricity and thermal energy, enhancing energy recovery from organic waste. Additionally, the unit includes algae cultivation, which utilizes $CO_2$ from biogas, contributing to biomass generation and environmental sustainability.

- Design Specifications

Table 3
summarizes the key design parameters of the simulated micro-digestion unit:

| Variable | Value |
|---|---|
| Process feed flowrate (t/d) | 1 |
| TS% process feed | 25–30% |
| TS% digester feed | 10–12% |
| TS% liquid digestate | 4–5% |
| TS% solid digestate | 25–30% |
| Fraction of liquid digestate recycled to the digester | 66.7% |
| Digester temperature (°C) | 37 |
| Expected biogas production ($Nm^3/d$) | 180 |
| Produced electrical power (kWe) | 15 |
| Produced thermal power (kWt) | 20 |
| Off-gas temperature (°C) | 257 |
| Liquid digestate P concentration (mgP/L) | 50–80 |
| Liquid digestate N concentration (mgN/L) | 2500–3000 |
| Liquid digestate pH | 7–8 |
| Note: TS% = Total Solids content. | |

• Concluding Remarks

This case study demonstrates the value of advanced process simulations in assessing biogas unit feasibility in urban environments. The integrated modeling of AD, CHP co-generation, and algae cultivation provides insights into technical performance, energy efficiency, and environmental benefits. The results offer a practical reference for stakeholders evaluating similar small-scale biogas projects, supporting informed decision-making regarding sustainable waste management and renewable energy generation (Thiriet et al., 2020).

# 4.3 Biogas Unit in a Rural Area in Zimbabwe

Zimbabwe faces a significant reduction in electricity supply due to decreased output at the Kariba hydropower station, caused by low water levels in the dam, as well as reduced performance of aging thermal power plants, resulting in increased load shedding. In response, the Energy Regulatory Authority (ERA) has engaged multiple stakeholders to explore solutions to the country’s energy deficit (ZERA, 2022). Among potential renewable energy sources, biomass waste represents a cost-effective option, offering lower investment and operational costs compared to wind and solar energy (Kaifa & Parawira, 2019; Kajau & Madyira, 2019; Shonhiwa et al., 2023; Shonhiwa et al., 2024).

Although off-grid rural farmers generate substantial organic waste suitable for anaerobic digestion (AD), limited information and awareness prevent widespread adoption of biogas technologies, leaving many communities “energy poor.”

- Techno-Economic Assessment of a Small-Scale Biogas Unit

This case study evaluates the feasibility of a small-scale biogas power plant (MBEP) on a typical rural farm in Zimbabwe. The analysis considered available biomass, estimated biogas production, digester selection, and generator sizing. The proposed MBEP processes 452 tons of organic waste to produce 435,350.7 kWh of combined thermal and electrical energy annually (Borges & Díaz, 2012).

- Biogas Composition and Applications

Biogas produced from AD consists primarily of methane (50–75%) and carbon dioxide (25–45%), with minor amounts of hydrogen sulfide, water vapor, ammonia, siloxanes, oxygen, carbon monoxide, nitrogen, and volatile organic compounds. Purification and upgrading technologies can enhance the energy content and usability of biogas for cooking, electricity generation, and as a substitute for fossil fuels (ZERA, 2022 ; Odejobi et al., 2023).

- Contribution to Sustainable Development Goals (SDGs)

The deployment of MBEPs contributes directly to multiple SDGs by integrating energy production with sustainable agricultural practices. Table 4 summarizes the potential impacts across nine SDGs (Logan & Visvanathan, 2019; Shonhiwa et al., 2023; Shonhiwa et al., 2024):

Table 4
Contribution of Anaerobic Digestion (AD) to Meeting the Sustainable Development Goals (SDGs)

| |
|---|
| **SDG 2 – End hunger, achieve food security and improved nutrition and promote sustainable agriculture**<br><br>**The sludge from AD can be used as an organic fertilizer, which amends the soil and increases crop yield. Using sludge also reduces weeds' growth, which is enhanced by using raw animal manure in the field.** |
| **SDG 3 – Ensure healthy lives and promote well-being for all at all ages**<br><br>The use of biogas reduces indoor air pollution by avoiding the use of biomass in its traditional form such as firewood and cow dung. Thus, air pollution–linked diseases are prevented. It also prevents bad smells from pit latrines used on the farm and biomass decomposing in landfills. |
| **SDG 5 – Achieve gender equality and empower all women and girls**<br><br>Women and children spend less time collecting firewood and the freed time is used for productive activities and education for girls. |
| **SDG 6 – Ensure availability and sustainable management of water and sanitation for all**<br><br>AD prevents raw sewage from getting into water bodies, especially by seepage from latrines and wastewater, which may be passed to water bodies, thus reducing carbon loading. |
| **SDG 7 – Ensure access to affordable, reliable, sustainable and modern energy for all**<br><br>AD utilizes waste biomass, which at times is a health hazard, to produce biogas which can be used for various applications such as cooking, electricity production, and replacement of fossil fuels in farming activities. |
| **SDG 9 – Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation**<br><br>The farmer can be self-sufficient by using biogas from the farm's waste products to provide energy for all farming and household activities. The farmer can create short-term employment during the construction of the MBEP and long-term employment for running and maintaining the MBEP. Some entrepreneurial activities can grow because of the availability of modern energy services. |
| **SDG 11 – Make cities and human settlements inclusive, safe, resilient and sustainable**<br><br>AD leads to well-managed waste collection and treatment, which reduces the occurrence of decaying waste-borne diseases on the farm and reduces the emission of greenhouse gases (GHG), especially methane, from decomposing organic matter. |
| **SDG 13 – Take urgent action to combat climate change and its impacts**<br><br>AD contributes to the abatement of climate change by avoiding methane and nitrous oxide emission from decaying biomass waste and converting methane in biogas to carbon dioxide, which has a lesser global warming potential than methane through combustion when biogas is used as fuel. |
| **SDG 15 – Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**<br><br>AD helps in practising integrated farming, which supports the recirculation of nutrients. The use of biogas prevents the cutting down of trees for firewood, hence reducing deforestation. |

• Current Status of Biogas in Zimbabwe

By 2017, Zimbabwe had installed 650 family digesters, 48 institutional digesters, and 13 municipal digesters, predominantly using cow manure, pig waste, and sewage sludge. Common digester types include the Chinese dome, biogas latrine, Indian floating drum, and Carmatec digester, with applications mainly for cooking, lighting,

and space heating in livestock facilities. However, in some cases, biogas is vented directly to the atmosphere (De Cagalitan & Abundo, 2021).

- Concluding Remarks

This case study highlights the potential of small-scale biogas units to address energy poverty in rural Zimbabwe. By valorizing organic waste, AD units can enhance energy security, promote sustainable agriculture, and contribute to multiple environmental and social objectives. Strategic implementation, combined with farmer education and government support, is essential to realize the full benefits of biogas technology in rural communities.

# 5. CONCLUSIONS

The assessment of biofuels and waste management reveals a complex and multifaceted landscape. The main conclusions and recommendations from this study are summarized below:

- **Climate Change and Energy Security**

The literature review highlights the critical role of transitioning from conventional fossil fuels to biofuels. Given the accelerating impacts of climate change and the continuous increase in greenhouse gas emissions, biofuels provide an effective pathway to mitigate environmental impacts and enhance energy security.

- **Environmental Benefits and Challenges**

Biofuels such as biodiesel and bioethanol deliver substantial environmental advantages, including reductions in pollutants and decreased reliance on non-renewable resources. However, challenges remain, particularly regarding land use, water consumption, and biodiversity impacts, which must be carefully managed to ensure overall sustainability.

- **Technological Development and Innovation**

Technological advances have significantly improved the efficiency and viability of biofuels. Innovations in feedstock utilization, such as microalgae and pre-treated biomass, contribute to higher energy yields and more sustainable production processes.

- **Economic Sustainability**

The economic feasibility of biofuels depends on factors such as raw material costs, technological development, and government support. Techno-economic analyses and cost-benefit studies are essential to evaluate viability and guide investment decisions.

- **Waste Management and Circular Economy**

Effective waste management is a cornerstone of sustainable biofuel production. Processes such as anaerobic digestion enable the conversion of organic and urban waste into energy, aligning with circular economy principles by reusing resources as feedstock for biofuel production.

- **Policy and Regulatory Framework**

The transition to biofuels is strongly influenced by regulatory and legislative environments. Government incentives, tax breaks, and the establishment of international standards can accelerate adoption, while coordinated policies ensure environmental and economic compliance. In addition, targeted policy instruments such as feed-in tariffs for biogas electricity, financial incentives for waste-to-energy infrastructure, and integrated waste management strategies could further accelerate the deployment of biofuel technologies.

- **Social and Economic Impacts**

Large-scale biofuel production fosters employment opportunities and supports local economies, particularly in rural regions. Nevertheless, potential social impacts, such as shifts in land use and rising food prices, require careful planning and monitoring.

- **Prospects and Future Directions**

Ongoing research in biofuels is essential to address global challenges, including climate change and the sustainable use of natural resources. Technological advancement, combined with collaboration between research institutions and governments, will play a pivotal role in achieving a resilient and sustainable energy future. Future research should focus on improving techno-economic optimization models for small-scale biogas systems, particularly in rural communities, while also exploring the integration of biofuels into emerging decarbonization pathways in sectors such as transportation and maritime energy systems.

- **Confirmation through Case Studies**

The three case studies analyzed in this study reinforce these conclusions:

- El Alto, Bolivia: Despite abundant urban waste, incentives for biogas production are limited, and economic measures are needed to lower the Levelized Cost of Electricity (LCOE) for biogas.
- Northern Italy: Biofuel utilization is technically and economically feasible, provided that waste management is integrated with technological, environmental, economic, and social considerations.
- Rural Zimbabwe: Microalgae and biomass waste can generate sufficient biogas to satisfy local energy demands. Attention to potential environmental impacts, such as land-use changes and water pollution, remains crucial.

In summary, small- and medium-scale biogas units offer the potential to transform local energy systems by generating renewable energy from clean and sustainable feedstocks. While certain challenges exist, such as impacts on land, water, and biodiversity, they are not insurmountable. Through supportive policies, technological adoption, and proper management, the transition to biofuels is both feasible and beneficial for environmental, economic, and social sustainability. Furthermore, integrating biogas production with circular economy strategies and sustainable waste management systems can significantly enhance resource efficiency and reduce environmental impacts. Future research should focus on improving the techno-economic performance of decentralized bioenergy systems and exploring their role in supporting broader energy transition and decarbonization strategies.

## Declarations

# ACKNOWLEDGMENTS

This is not applicable.

**FUNDING**

The authors declare that no funds, grants, or other financial support were received during the preparation of this manuscript.

**AUTHORS' CONTRIBUTIONS**

Athanasios Dounavis: Conceptualization, Methodology, Investigation, Supervision, Writing – original draft, Writing – review & editing.

Gerasimoula Alexopoulou: Data curation, Formal analysis, Visualization.

All authors have read and agreed to the published version of the manuscript.

**ETHICAL APPROVAL**

This study did not involve human participants or animals, and therefore ethical approval was not required.

**CONSENT TO PARTICIPATE**

Not applicable.

**CONSENT TO PUBLISH**

Not applicable.

**COMPETING INTERESTS**

The authors declare that they have no known competing financial or non-financial interests that could have influenced the work reported in this paper.

**DATA AVAILABILITY STATEMENT**

No datasets were generated or analysed during the current study. The data supporting the findings are available from the corresponding author upon reasonable request.

**CLINICAL TRIAL NUMBER**

Not applicable.

## References

1. Acien FG, Molina E, Fernández-Sevilla JM, Barbosa M, Gouveia L, Sepúlveda C, Arbib Z (2017) Economics of microalgae production. Microalgae-Based Biofuels and Bioproducts: From Feedstock Cultivation to End-Products. Elsevier, pp 485–503
2. Agarwal AK (2007) Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog Energy Combust Sci
3. Ajdari S (2021) *Biomethanol Production and Use as Fuel*. European Technology and Innovation Platform Bioenergy. https://www.etipbioenergy.eu/images/ETIP_Bioenergy_Biomethanol_production_and_use_as_fuel.pdf
4. Al Seadi T (2008) Biogas Handbook. University of Southern Denmark, Esbjerg
5. Atabani AE, Silitonga AS, Badruddin IA, Mahlia TMI, Masjuki HH, Mekhilef S (2012) A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew Sustain Energy Rev 16:2070–2093
6. Atadashi IM, Aroua MK, Aziz A, Sulaiman AR, N.M.N (2013) The effects of catalysts in biodiesel production: A review. J Ind Eng Chem 19:14–26
7. Barbera E, Bertucco A, Nigam KDP, Kumar S (2022) Techno-economic analysis of a micro-scale biogas plant integrated with microalgae cultivation for the treatment of organic municipal waste. Chem Eng J 450:138323. https://doi.org/10.1016/j.cej.2022.138323
8. Bernard O, Rémond B (2012) Validation of a simple model accounting for light and temperature effects on microalgal growth. Bioresour Technol 123:520–527
9. Bertrand E, Dussap C-G (2022) First generation bioethanol: Fundamentals—definition, history, global production and evolution. In: Soccol CR, Pereira GAG, Dussap C-G, Vandenberghe LPS (eds) Liquid Biofuels: Bioethanol. Springer
10. Borges ME, Díaz L (2012) Recent developments on heterogeneous catalysts for biodiesel production by oil esterification and transesterification reactions: A review. Renew Sustain Energy Rev 16:2839–2849
11. Borras SM Jr., McMichael P, Scoones I (2010) The politics of biofuels, land and agrarian change: A special issue on biofuels. J Peasant Stud 37:575–592
12. Bušić A, Marđetko N, Kundas S, Morzak G, Belskaya H, Šantek MI, Šantek B (2018) Bioethanol production from renewable raw materials and its separation and purification: A review. Food Technol Biotechnol 56:289–311. https://doi.org/10.17113/ftb.56.03.18.554627
13. Chaturvedi S, Dave PN, Shah NK (2012) Applications of nano-catalyst in new era. J Saudi Chem Soc 16:307–325
14. Chisti Y, Karimi K (2022) Bioethanol production. Reference Module in Earth Systems and Environmental Sciences. Elsevier. https://doi.org/10.1016/B978-0-323-90386-8.00017-6
15. Cucchiella F, D'Adamo I, Gastaldi M (2019) Sustainable Italian cities: The added value of biomethane from organic waste. Appl Sci 9:2221
16. Czernik S, Bridgewater AV (2004) Overview of applications of biomass fast pyrolysis oil. Energy Fuels 18:590–598
17. De Cagalitan F, Abundo M (2021) A review of biohydrogen production technology for application towards hydrogen fuel cells. Int J Hydrog Energy

18. Dounavis AS, Ntaikou I, Kamilari M, Lyberatos G (2016) Production of advanced bio-based hydrogen-enriched methane from waste glycerol in a two-stage continuous system. Waste Biomass Valoriz 7:677–689. https://doi.org/10.1007/s12649-016-9538-9
19. Dounavis AS, Tasionas A (2019) Techno-economic analysis of olive oil mill waste valorization for energy production: A case study of Corfu. Environ Res Eng Manage 75(4):18–29. https://doi.org/10.5755/j01.erem.75.4.23072
20. Dounavis AS, Ntavos N, Kafasis P (2019a) Using an online platform for the improvement of industrial symbiosis and circular economy in Western Macedonia, Greece. Global NEST J 21(1):76–81. https://doi.org/10.30955/gnj.002735
21. Dounavis AS, Mai ST, Koumalas AI, Barampouti EMP (2019b) Leachates from landfill sites in Thessaloniki, Greece: Effect of aging. Environ Res Eng Manage 75(4):30–39. https://doi.org/10.5755/j01.erem.75.4.23073
22. Dounavis AS, Ntaikou I, Lyberatos G (2015) Production of biohydrogen from crude glycerol in an up-flow column bioreactor. Bioresour Technol 198:701–708. https://doi.org/10.1016/j.biortech.2015.09.072
23. Diaz C, Tapanes N, Camara T, Aranda D (2014) Glycerol conversion in the experimental study of catalytic hydrolysis of triglycerides for fatty acids production using Ni or Pd on $Al_2O_3$ or $SiO_2$. Renewable Energy 68:113–122
24. Divya D, Gopinath LR, Christy PM (2015) A review on current aspects and diverse prospects for enhancing biogas production in sustainable means. Renew Sustain Energy Rev 42:690–699
25. European Commission (2008) Directive 2008/98/EC on waste and repealing certain directives. Official Journal of the European Union
26. Garcia A (2014) Techno-economic feasibility study of a small-scale biogas plant for treating market waste in the city of El Alto. KTH School of Industrial Engineering and Management, Stockholm
27. Gebremariam SN, Marchetti JM (2017) Biodiesel production technologies: Review. AIMS Energy 5:425–457
28. Goria K, Kothari R, Singh H, Singh A, Tyagi VV (2022) Biohydrogen: Potential applications, approaches and hurdles to overcome. In: *Handbook of Biofuels*. Academic Press, pp. 399–418
29. Gu X, Wang Y, Li H, Wang S (2020) Characteristics of biohydrogen production and performance of hydrogen-producing acetogen by increasing normal molasses wastewater proportion in anaerobic baffled reactor. *Archaea* 2020, 8885662. https://doi.org/10.1155/2020/8885662
30. Hansen TL, Jansen JLC, Davidsson A, Christensen TH (2007) Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. Waste Manag 27:398–405
31. Hasan MM, Rahman MM (2017) Performance and emission characteristics of biodiesel–diesel blend and environmental and economic impacts of biodiesel production: A review. Renew Sustain Energy Rev 74:938–948
32. IEA Bioenergy (2022) The role of biogas and biomethane in the pathway to net zero. IEA Bioenergy
33. Inter-American Development Bank (2014) Programme for the implementation of integrated solid waste management in Bolivia. Inter-American Development Bank
34. IRENA (2018) Biogas for road vehicles: Technology brief. International Renewable Energy Agency, Abu Dhabi

35. Jingura RM, Matengaifa R (2009) Optimization of biogas production by anaerobic digestion for sustainable energy development in Zimbabwe. Renew Sustain Energy Rev 13:1116–1120. https://doi.org/10.1016/j.rser.2007.06.015
36. Kaifa J, Parawira W (2019) A study of the current state of biogas production in Zimbabwe: Lessons for Southern Africa. Adv Biotechnol Microbiol 11:60–68
37. Kajau G, Madyira D (2019) Analysis of the Zimbabwe biodigester status. Procedia Manuf 35:561–566. https://doi.org/10.1016/j.promfg.2019.05.079
38. Kalam MA, Masjuki HH (2002) Biodiesel from palm oil—An analysis of its properties and potential. Biomass Bioenergy 23:471–479
39. Logan M, Visvanathan C (2019) Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects. Waste Manag Res 37:27–39
40. Luque R, Davila L, Clark JH, Herrador JM (2009) Biofuels: A technological perspective. Energy Environ Sci 2:1030–1040. https://doi.org/10.1039/B807094F
41. Ma F, Hanna MA (1999) Biodiesel production: A review. Bioresour Technol 70:1–15
42. Mao C, Feng Y, Wang X, Ren G (2015) Review on research achievements of biogas from anaerobic digestion. Renew Sustain Energy Rev 45:540–555
43. Marchetti JM, Miguel VU, Errazu AF (2007) Possible methods for biodiesel production. Renew Sustain Energy Rev 11:1300–1311
44. Marchetti JM, Miguel VU, Errazu AF (2008) Techno-economic study of different alternatives for biodiesel production. Fuel Process Technol 89:740–748
45. Melis A, Happe T (2001) Hydrogen production: Green algae as a source of energy. Plant Physiol 127:740–748
46. Neto J, Komesu A, Martins L, Gonçalves V, Oliveira J, Rai M (2019) Third generation biofuels: An overview. Sustainable Bioenergy. Elsevier, pp 283–298
47. O'Connor S, Pillai S, Bartlett J (2020) Production of biodiesel using ionic liquids. Nanotechnology in Life Sciences. Springer, pp 245–269
48. Odejobi OJ, Ajala OE, Osuolale FK (2023) Review on potential of using agricultural, municipal solid and industrial wastes as substrates for biogas production in Nigeria. Biomass Convers Biorefinery 13:1567–1579. https://doi.org/10.1007/s13399-022-02613-y
49. Pahl G (2005) Biodiesel: Growing a New Energy Economy. Chelsea Green Publishing
50. Parawira W (2010) Biodiesel production from *Jatropha curcas*: A review. *Scientific Research and Essays*
51. Park JY, Wang ZM, Kim DK, Lee JS (2010) Effects of water on the esterification of free fatty acids by acid catalysts. Renewable Energy 35:614–618
52. Piadeh F, Offie I, Behzadian K, Rizzuto J, Bywater A, Cordoba-Pachon J, Walker M (2024) A critical review for the impact of anaerobic digestion on the sustainable development goals. J Environ Manage 344:119458. https://doi.org/10.1016/j.jenvman.2023.119458
53. Portillo E, Chávez A, Colín A, Romero R (2015) Qualitative characteristics of biodiesel obtained from sunflower oil. In: *Biofuels – Status and Perspectives*. InTech. https://doi.org/10.5772/59673

54. Riaño B, Molinuevo-Salces B, Parralejo A, Royano L, González-Cortés J, García-González M (2023) Techno-economic evaluation of anaerobic co-digestion of pepper waste and swine manure. Biomass Convers Biorefinery 13:7763–7774. https://doi.org/10.1007/s13399-021-01831-0
55. Scarlat N, Dallemand J-F, Fahl F (2018) Biogas: Developments and perspectives in Europe. Renewable Energy 129:457–472. https://doi.org/10.1016/j.renene.2018.03.006
56. Shonhiwa C, Mapantsela Y, Makaka G, Mukumba P, Shambira N (2023) Biogas valorisation to biomethane for commercialisation in South Africa: A review. Energies 16:5272. https://doi.org/10.3390/en16145272
57. Shonhiwa C, Mukumba P, Makaka G (2024) Techno-economic analysis of a mini biogas electricity plant (MBEP) for a typical farm in the Zimbabwean off-grid areas. Biomass Convers Biorefinery. https://doi.org/10.1007/s13399-024-05493-6
58. Singh P, Kalamdhad AS (2023) A comprehensive assessment of state-wise biogas potential and its utilization in India. Biomass Convers Biorefinery 13:12557–12579. https://doi.org/10.1007/s13399-021-02001-y
59. Sisto R, Sica E, Lombardi M, Prosperi M (2017) Organic fraction of municipal solid waste valorisation in southern Italy: The stakeholders' contribution to a long-term strategy definition. J Clean Prod 168:302–310. https://doi.org/10.1016/j.jclepro.2017.08.186
60. Thiriet P, Bioteau T, Trémier A (2020) Optimization method to construct micro-anaerobic digester networks for decentralized biowaste treatment in urban and peri-urban areas. J Clean Prod 243:118478. https://doi.org/10.1016/j.jclepro.2019.118478
61. Timilsina GR (2014) Biofuels in the long run: Global energy supply mix for transportation. Philosophical Trans Royal Soc A 372:20120323
62. Uddin MN, Wright MM (2023) Anaerobic digestion fundamentals, challenges and technological advances. Phys Sci Reviews 8:2819–2837. https://doi.org/10.1515/psr-2021-0068
63. Verma D, Fortunati E, Jain S, Zhang X (2019) Biomass, Biopolymer-Based Materials, and Bioenergy. Elsevier
64. Wang Z, Hu Y, Wang S, Wu G, Zhan X (2023) A critical review on dry anaerobic digestion of organic waste: Characteristics, operational conditions and improvement strategies. Renew Sustain Energy Rev 176:113208. https://doi.org/10.1016/j.rser.2023.113208
65. World Biogas Association (2016) The contribution of anaerobic digestion and biogas towards achieving the UN Sustainable Development Goals. World Biogas Association, London
66. Williams CL, Westover TL, Emerson RM, Tumuluru JS, Li C (2016) Sources of biomass feedstock variability and the potential impact on biofuels production. Bioenergy Res 9:1–14. https://doi.org/10.1007/s12155-015-9694-y
67. Zamorska-Wojdyła D, Gaj K, Hołtra A, Sitarska M (2012) Quality evaluation of biogas. Ecol Chem Eng S 19:77–87
68. ZERA – Zimbabwe Energy Regulatory Authority (2022) *Annual report: A decade of sustainable service in Zimbabwe*. Harare

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- floatimage1.png
- ResponsetoReviewersDr.AthanasiosDounavis1732026.docx