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ANALYSIS OF THE DEVELOPMENT OF TECHNOLOGY FOR PRODUCING ETHANOL FROM BIOMASS

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Abstract

Bioethanol is one of the most important liquid biofuels and is capable of significantly reducing fossil fuel consumption and greenhouse gas emissions. A wide range of raw materials are used for its production. First- and fourth-generation bioethanol is distinguished. The ethanol production process can be carried out using biological or synthetic technologies. Fermentation allows the production of ethanol from renewable raw materials, while synthetic production allows for a high-purity product, but requires the use of petrochemical raw materials. Process optimization includes, among other things, modernizing process water recovery systems, using biological methods involving algae, and integrating bioethanol production with other energy processes. Life-Cycle Assessment (LCA) indicates that greenhouse gas emissions from field fertilization and the high water consumption of the entire process remain a significant environmental issue. The use of bioethanol as a transport fuel additive is supported by European Union policy, while the first-generation bioethanol market is successfully developing in Brazil and its production is currently the cheapest. Bioethanol, especially second generation, is an important element of energy transformation, but its economic competitiveness requires further technological innovation and regulatory support.

Keywords: bioethanol, biomass, LCA, ethanol, synthesis, fermentation, distillation, environmental protection

Introduction

Biofuels are defined as fuels obtained from raw materials of plant and animal origin, as well as microorganisms. Bioethanol is a liquid fuel derived from agricultural crops such as grain, beets, and their waste, and is currently the most widely produced biofuel in the world. Its dominant role is unchallenged. Annual global ethanol production has exceeded 100 billion liters. The main suppliers of ethanol are the United States and Brazil (80% of global production). Ethanol production in Poland has also been steadily increasing for many years and has currently reached an annual production level of 0.6 billion liters, primarily due to the introduction of E10 gasoline with a 10% (v/v) bioethanol content. A pioneer in the use of ethanol as a fuel was American industrialist Henry Ford, who first promoted the use of pure ethanol in his cars, and then a more versatile fuel blend with a 10% ethanol content. Ethanol production can improve the fuel market balance by replacing some imported crude oil. It contributes to greenhouse gas reduction and is also a key element in building fuel security nationwide. The share of renewable energy consumed in the European Union has reached 23% thanks to the development of energy sources such as solar, wind, hydropower, geothermal, biomass, and biogas, as well as by reducing the use of non-renewable sources. Second- and fourth-generation biofuels are not widely used due to their high production costs (Smuga, 2011). The aim of this article is to highlight the importance of bioethanol as a second-generation fuel, present the raw materials necessary for ethanol production, optimize the energy process, and analyze its environmental performance.

Ethanol production technologies and raw materials needed for its production

Ethanol is used in many areas of human life. Its production is carried out from, among others, beets, potatoes, straw, sugarcane, agricultural waste, and forest waste (Guragain, Probst and Vadlani, 2015). An alternative source of fermentable sugars is microalgae. They belong to the group of thalophiles that live in aquatic and humid environments. The advantage of using this raw material is its unrivaled advantage compared to other methods of oil extraction (Jakóbiec and Wądrzyk, 2010). Algal biomass is characterized by a high content of ammonium compounds, which influences the course of methane fermentation; therefore their potential can be exploited as an additive to agricultural waste undergoing fermentation (Pasoń, 2022). Ethanol production is carried out using two main methods: biological (fermentative) technology based on the use of agricultural raw materials and microorganisms, and synthetic technology based on chemical reactions involving hydrocarbons of petrochemical origin. The choice of technology depends on the availability of raw materials, production costs, and the intended use of ethanol (Kazmi *et al.*, 2025). Biological technology is based on the ability of yeast of the Saccharomyces genus to convert simple sugars into ethanol and carbon dioxide through alcoholic fermentation. This method has been known for thousands of years and has formed the basis of the production of potable alcohol and, in recent decades, biofuels. First, the raw material must be prepared. It should be noted that sugary raw materials, such as molasses, sugar beets, and sugar cane, can be fermented directly, while starchy raw materials, such as potatoes, corn, and wheat, require prior saccharification using amylolytic enzymes. Glucose is decomposed. The process is conducted at 30–35°C, and the final ethanol concentration in the wort is typically 8–12%. Distillation and rectification are used to separate the ethanol from water and by-products. Ethanol with a purity of approximately 95–96% is obtained. In the case of bioethanol used as fuel, it is necessary to remove residual water, for example, by adsorption on molecular sieves (Syaera Hidzir *et al.*, 2014). Fermentation production uses renewable raw materials, which makes it environmentally friendly. Its disadvantages include relatively low efficiency and the dependence of costs on the prices of agricultural raw materials (Rudolf, Karhumaa and Hahn-Hägerdal, 2009). Synthetic technology is based on direct chemical reactions leading to the production of ethanol from hydrocarbons of petrochemical origin. This method is mainly used in the production of technical ethanol, used in the chemical and energy industries (Mohsenzadeh, Zamani and Taherzadeh, 2017). The most important synthetic process is the catalytic hydration of ethylene. This reaction occurs at a temperature of 250–300°C and under a pressure of 60–70 atm. The catalyst is phosphoric acid applied to a solid support. This process allows for obtaining high-purity ethanol with high yields (Clark, 2002). The second, currently marginal method is the catalytic reduction of acetaldehyde to ethanol using hydrogen and metal catalysts (e.g., Ni, Pt). Synthetic ethanol production is efficient and produces a high-purity product. However, its drawbacks include its dependence on non-renewable resources, such as crude oil and natural gas, and its larger carbon footprint compared to biological fermentation (Chowdhury *et al.*, 2025).

The availability of raw materials for bioethanol production varies. Specifically, agricultural waste such as straw is less used for bedding and animal feed, as a decline in livestock farming can be observed over the years.Cellulose has been an available resource on Earth for years, making it a great alternative for biofuels, since cellulose, which constitutes the structural material of plants, is more resistant to hydrolyzing factors. We can obtain it from the breakdown of perennial grasses and wood chips (Smuga-Kogut, 2015a).

Optimization of the technological process

The European Union is placing increasing emphasis on the use of natural resources as a potential energy source. For this reason, concepts are emerging to modernize the use of, for example, agricultural waste, which is an ideal replacement for traditionally extracted mine-derived raw materials. This is aimed, among other things, at optimizing energy production costs, for example, in industry (Owczuk, Rogulska and Bogumił, 2015). A study based on stabilization of fertilizer produced from manure sludge subjected to methane fermentation showed that under anaerobic conditions, the carbon-to-nitrogen ratio increased dramatically during nitrogen losses during carbon mineralization processes. The temperature increased in the first two weeks of the study, stabilizing almost to its initial value after five weeks. Additionally, a change in pH to alkaline was observed under aerobic conditions, creating the possibility of continuing the food chain (Hermann and Uzar, 1993). Throughout the fermentation process, the process water is regularly irrigated, which promotes efficient decomposition of organic substances. Industry requires water for purification or cooling during individual production stages, which is why it is so important to recycle process water, which, with the use of appropriate filters, is suitable for reuse. This is achieved through the following processes:

- reverse osmosis, which involves passing water through a membrane under high pressure, separating heavy metals, salts, and viruses from usable water
- ion exchange, which reduces the salinity of the water by replacing calcium and magnesium ions with sodium ions. Special softeners are used for this purpose.

Global biofuel production is strongly influenced by political decisions. Despite this, the European Union has for many years been implementing directives aimed at improving the use of, for example, second-generation biofuels based on hydrogen biochemistry (Smuga-Kogut, 2015b). By comparison, Brazil has been using first-generation biofuels based on sugarcane biomass for many years, which are competitive on the global market (Golisz, 2014).

Life cycle assessment (LCA) and environmental performance analysis

LCA (Life Cycle Assessment) as an assessment of the environmental impact of product production is crucial because it allows determining whether individual production stages comply with European Union directives (Hackenhaar et al., 2024). During the fermentation process, glucose is broken down by enzymes, e.g., yeast, into ethanol and carbon dioxide. The sugar to CO_2 ratio is 1:2 (Pepin and Marzzacco, 2015). A detailed description of the life cycle of bioethanol production should take into account the type of fertilization of the components, as N_2O emissions are important for estimating the amount of CO_2 released (Reijnders and Huijbregts, 2011; Numjuncharoen *et al.*, 2015). The issue of water consumption in the entire life cycle assessment covers not only water used for purification processes but also irrigation of croplands, from which agricultural waste is then used to produce bioethanol (Chiu, Shiang and Lin, 2015). Energy consumption in the fermentation process does not end with the supply of steam and thermal energy for the distillation process; it also includes the electrical energy used by machinery and the mechanical energy of agricultural vehicles (Hailu, 2020). Current methods for obtaining ethanol, broken down by generation, are as follows:

G1 - first-generation bioethanol (fermentation of raw materials: grain, sugar, corn). Production cost: \$0.4-0.6/dm^3. Yield: 350 dm^3 of bioethanol/dm^3 of grain.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2\uparrow \quad (1)$$

G2 - second-generation bioethanol (fermentation of non-food raw materials, inedible plant parts: straw, wood, glycerol, plant residues, lignocellulose). Production cost: 0.8-1.2 USD/dm^3. Cellulose predominates in the lignocellulosic raw material (30-60% dm). Cellulose $(C_6H_{10}O_5)n$ is a polysaccharide composed of thousands of glucose molecules linked by glycosidic bonds (approximately 7 µm). The second most quantitative polysaccharide is hemicellulose (20-50% dm). Hemicellulose, unlike cellulose, is not a homogeneous polymer. It does not have a single, specific formula because it is a heterogeneous mixture of various polysaccharides, such as hexosans and pentosans. The hemicellulose structure contains branches with short side chains containing various simple sugars: pentoses (xylose, rhamnose, arabinose), hexoses (glucose, mannose, galactose), and others. Hemicelluloses are relatively easily hydrolyzed. Waste biomass is subjected to pretreatment, chemical hydrolysis, and enzymatic hydrolysis, which releases simple sugars, which can then be subjected to fermentation processes. Cellulose hydrolysis:

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 \quad (2)$$

G3 - Third-generation bioethanol (culturing of microalgae or single-cell microorganisms derived from eukaryotes and prokaryotes (cyanobacteria, such as Cyanidium caldarium or Synechococcus). Production cost: \$2-4/dm^3 (Robak and Balcerek, 2018).

G4 - Fourth-generation bioethanol (genetically modified plants, microorganisms, CO_2), highest production cost: \$3-5/dm^3, but may be the most profitable in the future**.**

Other methods of producing ethanol include:

– Synthetically or through fermentation of syngas (syngas → ethanol). Syngas, a mixture of H_2, CO, and CO_2, is obtained from biomass using bacteria such as Clostridium ljungdahlii, which convert the syngas into ethanol and acetic acid through bioconversion. The ethanol is then separated and purified from the fermentation broth. Syngas fermentation has the potential to produce a variety of renewable products. However, a disadvantage is the low efficiency of this process. A more comprehensive understanding of microbial interactions within natural microbial consortia is necessary (Neto *et al.*, 2025).

– hydration of ethylene, a petroleum refining product (300°C, 300 atm, cat. H_3PO_4) by adding water (electrophilic addition) to the double bond (Broda, Yelle and Serwańska, 2022):

$$CH_2 = CH_2 + H_2O \rightarrow CH_3\text{-}CH_2\text{-}OH \quad (3)$$

The table below presents the most important information about first-generation bioethanol.

Table 1. Characteristics of first-generation bioethanol

First generation bioethanol	
Raw material	Sugar cane, beets, potatoes
Renewability	Yes, but at the expense of food use
Source	Food biomass
Process	hydrolysis and fermentation in separate stages
CO_2 emissions	Low from the fermentation process but high from fertilization
Water consumption	Large, field irrigation, process water
Energy consumption	High heat demand for distillation
Impact/contact with soil	High, soil degradation, erosion, fertilization, competition with food
Cost	The cheapest technology so far, high efficiency, good energy balance: 0.4 - 0.6 USD/dm^3

Data show that this is the cheapest method of producing ethanol, but it is highly energy-intensive and water intensive. CO_2 emissions are relatively low. The most important data on second-generation bioethanol are presented in Table 2.

Table 2. Characteristics of second-generation bioethanol

Second generation bioethanol	
Raw material	Agricultural waste, wood, straw
Renewability	Yes, more sustainable
Source	Non-food biomass
Process	Chemical, physical, or enzymatic decomposition of biomass
CO_2 emissions	Low, because fertilized crops are not taken into account
Water consumption	Smaller, minor irrigation, mainly process water
Energy consumption	Higher energy consumption of the process (hydrolysis, enzymes)
Impact/contact with soil	Low impact – waste-based raw material, lower risk of erosion
Cost	Expensive enzymes, but the technology is getting cheaper: 0.8 - 1.2 USD/dm^3

From the information presented, it can be concluded that, unlike first-generation bioethanol, second-generation bioethanol is quite expensive. Water consumption is lower than in the previous method. Table 3 presents syngas fermentation data.

Table 3. Characteristics of ethanol from synthesis gas

Synthesis gas	
Raw material	Syngas from biomass or coal, gas
Renewability	No, unless it's from biomass
Source	Biomass or fossil fuels
Process	Gas fermentation by bacteria, catalytic synthesis of ethanol (catalysts: Zn, Cu),
CO_2 emissions	If biomass is used, the emissions are low; if coal is used, the emissions are high.
Water consumption	Low, process water only
Energy consumption	Medium, high pressure catalytic process, or gas fermentation
Impact/contact with soil	Minimal if syngas is from waste or wood
Cost	Operationally inexpensive, but investment-intensive. Technology in its early stages.

The water consumption with this method is low and the water consumption is moderate. Contact with the soil is minimal. Table 4 presents the most important information on ethylene hydration.

Table 4. Ethylene hydration

Ethylene hydration	
Raw material	Ethylene from crude oil or natural gas
Renewability	No, because it is dependent on fossil fuels.
Source	Fossil fuels (non-renewable)
Process	Hydration, supported H_3PO_4 catalyst, 250–300°C
CO_2 emissions	High in petrochemicals and high in energy
Water consumption	Low, process water only
Energy consumption	Moderate (catalytic reaction, but energy upstream to ethylene)
Impact/contact with soil	No impact on soil, but impacts from oil/gas extraction
Cost	One of the cheapest methods, but dependent on the price of ethylene from oil/gas

This is one of the cheaper methods, with moderate energy consumption and low water consumption. It also has no impact on the soil.

Conclusions

In summary, biofuels represent an important alternative to fossil fuels, and bioethanol derived from agricultural raw materials and waste plays a particularly important role. First-generation bioethanol is derived from starch and sugar crops (to date, accounting for as much as 96% of global production) and second-generation bioethanol (3% of global production) from lignocellulosic biomass or microalgae. The latter is characterized by greater environmental efficiency but high costs. Ethanol can be produced biologically, based on yeast fermentation, or synthetically, primarily through the catalytic hydration of ethylene. The biological process relies on renewable raw materials, while the synthetic process provides high efficiency but relies on petrochemicals and generates a larger carbon footprint. Technology optimization includes, among other things, process water recovery, the use of agricultural waste, and the development of second-generation bioethanol. The future of bioethanol depends on technological innovations and regulatory support that will enable its broader application in a low-emission economy.

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