บรรณาธิการปริทัศน์/Editorial Corner

กระบวนการผลิตเอทานอลในรูปแบบเจเนเรชันที่หนึ่งถึงสี่เพื่อการพัฒนาที่ยั่งยืน
Ethanol Production From First-Generation to Fourth-Generation Technologies for Sustainable Development

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ศูนย์วิศวกรรมการกลั่นชีวภาพและกระบวนการอัตโนมัติ บัณฑิตวิทยาลัยวิศวกรรมศาสตร์ไทย-เยอรมันนานานาชาติสิรินธร มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าพระนครเหนือ

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Bioethanol is a renewable, sustainable fuel derived from biological sources, such as plants, primarily through the fermentation of sugars found in crops like sugarcane, corn, wheat, and other biomass materials. Bioethanol offers a promising alternative to conventional fossil fuels, helping to reduce greenhouse gas emissions and decrease reliance on non-renewable energy sources. Produced through biological processes, bioethanol can be blended with gasoline for combustion engines or used in its pure form for energy generation. It represents a critical component in the transition toward greener energy solutions, aligning with global efforts to combat climate change and promote sustainable development [1].

The benefits of bioethanol extend beyond environmental aspects. It also stimulates rural economies by creating demand for agricultural products, supporting local farming communities, and fostering technological innovation in the renewable energy sector. As a renewable energy source derived from biomass, bioethanol aligns with several Sustainable Development Goals (SDGs) established by the United Nations [2], including SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land) [3]. These goals aim to address global challenges, promote sustainability, and improve the quality of life worldwide.

However, despite its potential benefits, ethanol production faces several challenges, ranging from environmental and economic concerns to technical

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and social issues. Major challenges include competition for agricultural land, which can drive up food prices and lead to deforestation; the high demand for water and energy required for cultivation and processing; and greenhouse gas emissions associated with production [4]. Additionally, the efficiency of converting biomass to ethanol is often limited by the availability of suitable feedstocks and technological constraints. Addressing these challenges is essential for making ethanol a more sustainable and viable alternative to traditional fuels.

Bioethanol production has evolved significantly over time, with varying choices of feedstocks, methods, and technologies across different eras. Bioethanol production involves several steps, from selecting suitable feedstocks to processing and production. The production of ethanol can be categorized into four generations: 1st Generation (1G) bioethanol: This generation uses feedstocks primarily composed of starches and sugars, such as sugarcane, corn, wheat, and oilseeds [5], [6]. It utilizes well-established fermentation technology to convert the sugars in these crops into alcohol, which can be used as a renewable energy source. Although 1G bioethanol offers an alternative to fossil fuels and helps reduce greenhouse gas emissions, it raises concerns about food security, land use, and environmental impacts due to its reliance on agricultural crops and intensive farming practices.

2nd Generation (2G) bioethanol production: This generation involves producing ethanol from non-food feedstocks such as agricultural residues (e.g., corn stover, wheat straw, bagasse), forest residues, and dedicated energy crops (e.g., Napier grass). Unlike 1G bioethanol, which relies on edible crops, 2G bioethanol uses lignocellulosic biomass, which is abundant and does not compete directly with food production. The process involves more complex biochemical and thermochemical technologies to effectively break down lignin and convert the cellulose in biomass into fermentable sugars for ethanol production [7]. Chemical processing is crucial due to the challenging nature of the cell walls in these feedstocks, which can be difficult to break down. Incomplete pretreatment can lead to reduced yields and lower ethanol production [8], [9]. Although 2G bioethanol is a more sustainable option by reducing reliance on food crops and utilizing waste materials, it faces challenges such as high production costs, complex processing technologies, and lower overall conversion efficiency.

3rd Generation (3G) bioethanol production: This represents a significant advancement in biofuel technology, focusing on the use of algae feedstocks. Unlike 1G and 2G bioethanol, which rely on plant biomass and agricultural residues, 3G bioethanol leverages the unique properties of algae, which can produce high quantities of biomass from CO_2, sunlight [10], and water. Algae typically lack cell walls, making them easier to process. The primary appeal of using algae and microorganisms for 3G bioethanol production lies in algae's rapid growth rates, their ability to be cultivated on non-arable land where other crops cannot grow, and their potential to utilize CO_2 from industrial processes. The production process involves cultivating algae in photobioreactors or open ponds, harvesting the biomass, and then converting it into bioethanol through fermentation or other biochemical processes. Additionally, algae can produce fats that can be converted into biodiesel, making 3G bioethanol a versatile biofuel option. The advantages of 3G bioethanol include higher bioethanol yields per unit area compared to terrestrial plants, reduced competition with agricultural crops for arable land, and CO_2 absorption, which helps to mitigate greenhouse gas emissions. Ongoing research and development efforts focus on improving the efficiency and economic feasibility of this advanced biofuel, while also addressing the potentially higher costs associated with the production equipment compared to 1G and 2G bioethanol.

4th Generation (4G) bioethanol production: it represents the latest evolution in biofuel technology, combining advanced techniques and renewable resources to create a more sustainable and efficient bioethanol production process. 4G bioethanol aims to overcome the limitations of previous methods by incorporating a variety of new strategies and technologies. By using non-food biomass, such as agricultural waste, municipal waste, and specialized energy crops that do not compete with food supplies, 4G bioethanol helps resolve the food vs. fuel debate and reduces competition for land and resources. Advanced technologies, such as synthetic biology, genetic engineering, and novel fermentation processes, are employed to increase the efficiency of bioethanol production [11]. These technologies allow the use of a wider variety of feedstocks and improve the processing methods, resulting in higher yields and lower production costs. A key feature of 4G bioethanol is its focus on Carbon Capture and Utilization (CCU), which involves capturing CO_2 emissions from the production process and reusing them as feedstocks for bioethanol production or other industrial applications, thereby reducing the overall carbon footprint and aligning with SDGs. Additionally, 4G bioethanol production aims to optimize every stages of the process from the initial processing of raw materials to fermentation and distillation by enhancing enzyme technologies, fermentation microorganisms, and separation techniques to improve overall efficiency and sustainability.

The increasing energy demand has driven research aimed at developing and improving biofuel production methods that have minimal environmental impact and align with the principles of the SDGs. The choice of feedstock for ethanol production is crucial, and the selection of materials in each generation has sparked debates about the use of agricultural products, competition in agriculture, and the demand for natural resources. This has led to the evolution of ethanol production methods from 1G to 4G, each with its advantages and disadvantages. The challenges in bioethanol production are multifaceted. Third-generation biofuel technology has yet to be fully commercialized due to its relatively high costs. Therefore, there is a need to explore more cost-effective and efficient conversion technologies. Fourth-generation biofuels require further study in areas such as biology, genetic engineering, pretreatment processes, and efficient fermentation. Research is also needed to identify microorganisms capable of effectively fermenting both C5 and C6 sugars [12]. Strains resistant to inhibitors are critical for the process, and if natural feedstocks are studied and found compatible with natural processes, the biofuel production process may be considered successful.

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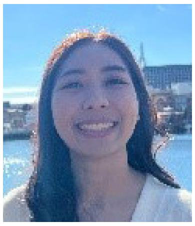

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