บรรณาธิการปริทัศน์/Editorial Corner

ความท้าทายและกลยุทธ์ในการพัฒนากระบวนการกลั่นทางชีวภาพตามหลักเศรษฐกิจชีวภาพที่ยั่งยืน
Biorefinery Challenges and Strategic Solutions for a Sustainable Bioeconomy

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ศูนย์วิศวกรรมโรงกลั่นชีวภาพและกระบวนการอัตโนมัติ สาขาวิชาวิศวกรรมเคมีและการจัดการ บัณฑิตวิทยาลัยวิศวกรรมศาสตร์นานาชาติสิรินธรไทย-เยอรมัน มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าพระนครเหนือ

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Biorefining is the sustainable processing of natural biomass into a wide range of marketable products and energy. A biorefinery integrates various processes and technologies to convert biomass into valuable products, aligning with the zero-waste concept [1]. Over the past few decades, biorefinery processes have been at the forefront of sustainability, offering an alternative to traditional non-renewable fuel sources. As global energy reserves continue to deplete due to population growth and rising consumption, biorefineries have played a transformative role in reshaping the energy sector with sustainable solutions.

Recognizing the urgency of sustainable development, the United Nations Development Program (UNDP) has emphasized the importance of the Sustainable Development Goals (SDGs) in enabling global communities to meet their needs while minimizing environmental impact [2]. Biorefineries help mitigate climate change, reduce dependence on fossil fuels, promote circular economy practices, and support economic growth across various sectors (Figure 1). Specifically, biorefineries align with key SDGs, including Affordable and Clean Energy (SDG 7), Industry, Innovation, and Infrastructure (SDG 9), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13). Additionally, their success underscores the necessity of collaboration between institutions, governments, communities, and industries, reinforcing the importance of Partnerships for the Goals (SDG 17) [3].

การอ้างอิงบทความ: Pooja Ranganayaki Anand, อภิญญา ขาวล้วน และ มาลินี ศรีอริยนันท์, "ความท้าทายและกลยุทธ์ในการพัฒนากระบวนการกลั่นทางชีวภาพตามหลักเศรษฐกิจชีวภาพที่ยั่งยืน," *วารสารวิชาการพระจอมเกล้าพระนครเหนือ*, ปีที่ 35, ฉบับที่ 4, หน้า 1–4, เลขที่บทความ 254-007753, ต.ค.–ธ.ค. 2568.

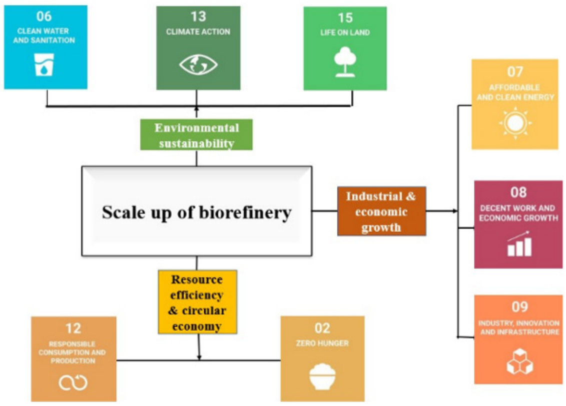

Figure 1 The Sustainable Development Goals (SDGs) relevant to the need for scale-up in biorefinery.

The biorefining process offers a sustainable solution to support the circular economy model by utilizing waste materials. Additionally, the use of biomass as feedstock contributes to carbon sequestration through plant growth [4]. These benefits make biorefineries a key enabler in the transition toward a net-zero carbon economy. The valorization of biomass into various bio-based products serves as one of the most effective pathways for achieving carbon-neutral alternatives. To promote the utilization of this concept, the biorefinery process has been facing several key challenges arising from various concerns. One major issue is the harvesting and preservation of raw materials, especially agricultural wastes before industrial processing. Collecting agricultural residues in sufficient quantities can be difficult due to seasonal variations and environmental factors that affect crop yields, leading to inconsistencies in raw material quality. Long-term biomass storage is a potential solution; however, it comes with challenges such as the need for extensive storage space and the gradual degradation of biomass over time [5]. Secondly, land availability and crop diversity play a crucial role in biorefinery production. Since most raw materials are derived from field crops, large areas of land are required for cultivation. Soil nutrient composition directly impacts raw material quality, while variations in plant growth affect the efficiency of biomass conversion into final products [6]. Thirdly, the complexity of the biorefinery production process presents significant technical challenges. Many raw materials, especially lignocellulose, exhibit resistance to conversion, requiring multiple processing steps to break down their chemical structures. These steps include biomass pretreatment, washing, and neutralization, all of which demand substantial amounts of water and energy [7]. As a result, high production costs and resource consumption can impact future market prices.

Furthermore, to transfer the biorefining process from research to commercialization, scaling up is a hurdle of its progress. The critical step is biomass pretreatment, which assists in the disintegration of complex polymeric structures of biomass. The conventional pretreatment methods are often difficult to implement on an industrial scale due to high costs and operational complexities [8]. Chemical pretreatment typically requires expensive reagents, while physical methods are highly energy-intensive. Additionally, biomass washing after chemical pretreatment demands large volumes of water at an industrial level, resulting in large amounts of wastewater.

Competition for fertile land is a key challenge in sustainable biomass production, particularly due to conflicts with the food and feed industries.

Ensuring a balance between biomass cultivation and agricultural needs is essential for long-term sustainability [9]. The diversity of raw materials and variability in biomass composition present both opportunities and challenges for biorefineries. One major advantage is their ability to produce a wider range of products than traditional oil refineries while utilizing a more diverse array of feedstocks. However, this diversity also impacts the design and optimization of mechanical and chemical pretreatment processes, which are crucial preparatory steps before subsequent thermochemical or biochemical conversions. Multi-feedstock or mixed biomass helps to mitigate the impact of raw material price fluctuations, which is particularly important for small-scale processes, as their economic feasibility is less affected by such changes [9]. Fluctuations in raw material prices can create challenges for industrial production, often forcing adjustments in feedstock selection or reductions in production scale. These disruptions can, in turn, impact the industry's ability to meet consumer demand in quantities.

To ensure economic and technical viability, a techno-economic analysis must be conducted during process design, along with a feasibility study before scaling up. Process integration opportunities, such as Simultaneous Saccharification and Fermentation (SSF), should be identified during design, as combining steps can reduce overall operating costs and improve efficiency. Additionally, the use of engineered microbes can enhance product yield and improve process resilience by withstanding higher temperatures [10]. The incorporation of immobilized enzymes and microbes offers another promising strategy, as they are reusable and contribute to cost-effective, and sustainable production. Pretreatment processes must be optimized for various biomass types to ensure consistent sugar yields. Blending biomass from different sources can help improve feedstock composition, while high-quality control sensors and Artificial Intelligence (AI) can be used to monitor and adjust feedstock properties in real time, minimizing composition fluctuations. Advanced simulation software, such as Computational Fluid Dynamics (CFD), can optimize reactor design by improving aeration and mixing efficiency. The use of membranes during fractionation steps enhances product purity by eliminating the need for multiple downstream processing steps. This also reduces wastewater, as filtered water can be recirculated into the system. Furthermore, by-products like lignin can be converted into value-added products, such as vanillin and polyphenols, while residual biomass can be utilized for biogas production, supporting energy recovery and circular economy principles. Collaboration with other industries can further enhance sustainability through an integrated circular economy approach. Many governments offer incentives, subsidies, and policy support for bio-based industries, making these processes more cost-effective. Additionally, conducting a Life Cycle Assessment (LCA) is essential for evaluating sustainability and ensuring an effective scale-up strategy. These strategies collectively contribute to the development of a more efficient, cost-effective, and environmentally sustainable bioprocessing industry. By integrating innovative technologies and strategic collaborations, the transition toward a more resilient and circular bioeconomy can be successfully achieved.

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