Process Integration and Coupling to Improve the Biorefinery Process

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Biomass is a naturally renewable resource with wide distribution and huge annual output. It is the most abundant renewable organic resource in the world. Biorefinery can be defined as a processing system that converts biomass into a full range of energy products and chemical materials through a series of physical, chemical, and biological conversion treatments. It provides a practical technical route for reducing global dependence on fossil energy, mitigating the greenhouse effect, and promoting the green transformation of the global chemical and energy industry. To fully utilize the components of biomass, the biorefinery process generally comprises complex processing units and procedures, which results in low production efficiency and high investment. Process integration and coupling can effectively streamline its procedures and reduce the number of processing units. This can greatly enhance its production efficiency and reduce investment, thus improving its process economy. In recent years, a variety of innovative integration and coupling strategies have been developed in the biorefinery process. However, current process integration and coupling still face multiple practical challenges. This editorial will provide a brief discussion on the use of process integration and coupling in the biorefinery process.

DOI: 10.15376/biores.21.4.9316-9318

Keywords: Biorefinery process; Process integration; Coupling; Process economy

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Biorefinery: A Practical Path for Reducing Global Dependence on Fossil Energy and Achieving Carbon Neutrality Goals

Biomass is a naturally renewable resource that has a wide distribution and huge annual output. It is estimated that its annual output reached about 170 billion metric tons globally. It is the most abundant renewable organic resource in the world (Li 2019). Different from fossil energy, the carbon released during an ideal, perfectly efficient utilization of biomass is the same amount as the carbon absorbed by biomass during growth, so it has potential to approach a closed carbon cycle, which will not increase the net carbon emission in the atmosphere. This characteristic makes biomass energy one of the ideal ways to aim for carbon neutrality (Li 2019; Zhang *et al.* 2023). At the same time, biomass can also produce a variety of high-value chemical products and energy products through different conversion paths, covering liquid biofuels, bulk chemicals, functional materials, and other products that are currently mainly derived from fossil resources, which can replace fossil resources to a large extent and realize the sustainable supply of related products (Li 2019; Zhang *et al.* 2023; Xv *et al*. 2026a). As the core technical approach to

realize efficient utilization of biomass, the development of biorefinery is of great strategic significance for building a new sustainable green industrial system. The current global transformation of energy and chemical industry urgently requires continuous innovation and large-scale application of biorefinery technology (Bastidas-Oyanedel and Schmidt 2019). However, the large-scale promotion of existing biorefinery technologies is still facing great challenges. To achieve the full-component high-value utilization of biomass, the biorefinery process often involves complex processing units and procedures, which leads to low production efficiency and high investment (Bastidas-Oyanedel and Schmidt 2019; Zhu *et al*. 2026a,b). Process integration and coupling provide a useful technical method to simplify the procedures and reduce the number of processing units. It has potential to greatly enhance the production efficiency and reduce investment in capital equipment, thus improving the process economy.

Use of Process Integration and Coupling in the Biorefinery Process

Process integration and coupling used in the biorefinery process have made great progress in recent years, and a variety of innovative integration and coupling strategies have been developed in the biorefinery process (Bastidas-Oyanedel and Schmidt 2019; Xv *et al*. 2026b; Zhang *et al*. 2026; Zhu *et al*. 2026b). There are quite a lot of successful examples, such as the coupling of pretreatment and enzymatic hydrolysis processes, the integration of saccharification and fermentation, the integration of catalysis and separation, and the coupling of different biomass conversion paths to realize the co-production of multiple products (Bastidas-Oyanedel and Schmidt 2019; Xv *et al*. 2026b; Zhang *et al*. 2026; Zhu *et al*. 2026b). At present, common integration and coupling strategies in biorefinery processes can be roughly divided into three categories: integration between different conversion processes, coupling of reaction and separation units, and coupling of biomass refinery with other industrial processes. Integration between different conversion processes can realize the cascade utilization of different components of biomass, maximize the value of each component, avoid repeated separation and treatment of intermediate products, and simplify the procedures and reduce the number of processing units, thereby reducing energy consumption and production cost. The coupling of reaction and separation units can break the reaction equilibrium limitation in real time, improve the reaction conversion rate and product yield, and also omit the independent separation equipment for intermediate products, which significantly reduces equipment investment. The coupling of biorefinery with other industrial processes can realize the mutual utilization of energy, materials and by-products between different production systems, improve the overall resource utilization efficiency, and reduce the overall carbon emission of the whole industrial chain (Bastidas-Oyanedel and Schmidt 2019).

However, current process integration and coupling still face multiple practical challenges. Different processing units often differ significantly in operating parameters such as temperature, pressure, and pH, requiring additional adjustment processes that may offset part of the energy saving and consumption reduction benefits brought by integration. The compatibility of different materials and catalysts in coupled systems also puts forward higher requirements for material selection and process design, which increases the difficulty of process amplification and stable operation (Bastidas-Oyanedel and Schmidt 2019; Xv *et al*. 2026b; Zhang *et al*. 2026; Zhu *et al*. 2026b). In the future, deeper integration of intelligent process simulation and modular production technology is expected to break through these bottlenecks, by accurately simulating the interaction between various units and designing flexible modular connection schemes, further tapping the potential of

process integration and coupling, and promoting the continuous optimization and upgrading of the biorefinery industry.

Acknowledgments

This work was supported by Hubei Key Laboratory of Novel Reactor and Green Chemical Technology (NRG202410) and Graduate Innovative Fund of Wuhan Institute of Technology No: CX2025016.

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