Editorial Corner

The Missing Link: Bridging Laboratory Biorefineries to Industrial Implementation

Nida Arshad and Diana Jose*
Biorefinery and Process Automation Engineering Center, Department of Chemical and Process Engineering, The Sirindhorn Thai-German International Graduate School of Engineering, King Mongkut's University of Technology North Bangkok, Thailand

Pau Loke Show
Department of Chemical and Environmental Engineering, University of Nottingham, Malaysia, Semenyih, Selangor Darul Ehsan, Malaysia

* Corresponding author. E-mail: djdianajose2@gmail.com

DOI: 10.14416/j.asep.2025.11.002

Biorefineries are becoming foundational to a sustainable bioeconomy, converting biomass into fuels, chemicals, and materials while curtailing reliance on fossil feedstocks [1]. The global industrial biorefinery market is expected to exceed USD 48 billion by 2025, with steady expansion forecast through 2033 [2]. Yet, despite the proliferation of innovations at the laboratory scale, only a handful of technologies have migrated to commercial operation, such as novel pretreatment methods, microbial engineering, and hybrid conversion pathways [3]. This disconnect highlights a persistent paradox: while academic research is rich in breakthroughs, real-world industrial deployment remains sparse, constrained by economic, scaling, and policy uncertainties [4].

In the academic literature, the vast majority of biorefinery research remains confined to bench-scale experiments, for instance, novel pretreatment methods, enzyme optimization, microbial conversion pathways, and reactor design at milliliter-to-liter scale. While these studies provide valuable mechanistic insights and incremental improvements, they seldom incorporate scale-up constraints, such as mixing, heat transfer, solids loading, or process integration. Many proposals end at improved sugar yields or lab-scale fermentation, without even preliminary techno-economic or scale-up considerations [5]. Despite decades of innovation, only a small fraction of promising lab-scale processes ever reaches pilot or demonstration scale. Many ideas stall between academic proof of concept and industrial validation. Researchers highlight that, even in integrated biorefinery proposals, few authors document efforts to test at a pilot scale or engage in demonstration projects [4]. The impact of scale-up remains largely unexamined in recent work on agro-industrial by-product biorefineries. As a result, promising technologies remain untested under real-world constraints, such as feedstock heterogeneity, continuous operation, and maintenance demands, which further discourage industry translation [6].

Compounding the technical hurdles is a fragmented ecosystem of funding streams and research silos. Many grants support short-term, narrow-scope projects (exploring a new enzyme or solvent), thus only a few funds support full chain integration or long-term scale-up. In the U.S., for example, the Bioenergy Technologies Office (BETO) has established dedicated scale-up and systems integration portfolios. Therefore, competition for these funds is fierce, and overall funding remains limited. The 2023 Project Peer Review report even flagged that scale-up projects are underrepresented relative to basic research [7]. Internationally, national research agencies often lack mandates or budgets to underwrite capital-intensive pilot programs, resulting in fragmented advancements that seldom coalesce into coherent pilot demonstrations. Such a disjointed and underfunded framework acts as a brake on meaningful progression from lab to industry. Figure 1 highlights the critical bridges and existing gaps in the scale-up framework of biorefineries.

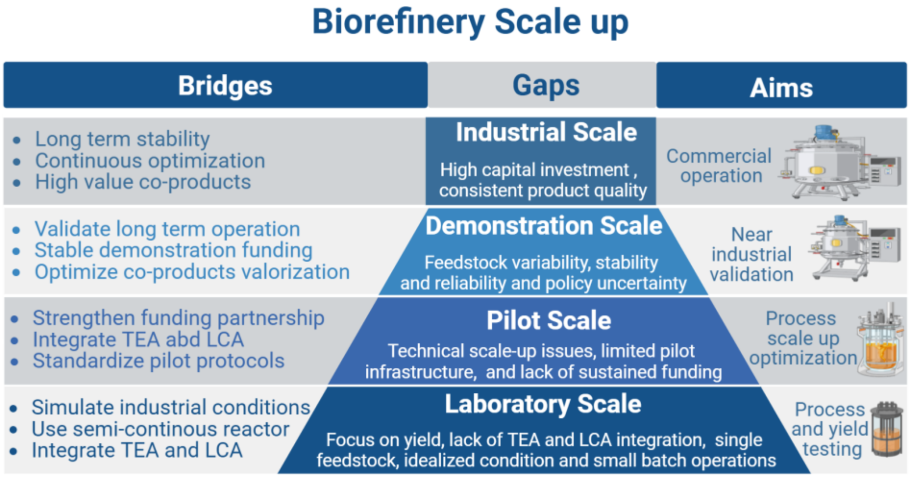

Figure 1: Bridges and gaps in biorefinery scale-up from lab to industrial scale.

Despite the rich landscape of laboratory advances, one of the greatest obstacles to scaling biorefineries is that many studies end at yield optimization and never progress to techno-economic analysis (TEA) and life cycle assessment (LCA) [8]. The pretreatment stage remains expensive, requiring aggressive chemicals, high pressure or temperature, and large water or catalyst inputs, which typically account for a disproportionately large share of capital and operating expenses [9]. Additionally, enzyme and energy demand further inflate costs. The cellulase cocktails, co-factors, and thermal inputs can represent 10–30% or more of total operating expenditure in biochemical conversion routes [10]. On the logistics side, the challenge of collecting, transporting, densifying, and storing bulky biomass from distributed sources incurs high costs and variability, which erodes margins before even entering a conversion plant [11]. Finally, even when a bioprocess is technically feasible, it often struggles to compete cost-wise with established petrochemical routes, especially when fossil feedstocks benefit from legacy infrastructure, economies of scale, and subsidies. Integrated reviews show that many promising lab results never quantify this gap, leaving commercial viability untested [12].

Pilot and demonstration scale efforts are a critical yet often neglected bridge between lab-scale promise and real-world impact, because only by operating under semi-industrial conditions can one validate stability, feedstock variability tolerance, process integration, and operational resilience. By lowering capital barriers and enabling multiple projects to access standardized scale-up platforms, they promote cross-sector collaboration and more efficient utilization of limited resources. In this collaborative matrix, universities, technology developers, industrial users, supply chain partners, and policymakers can co-develop and validate processes under realistic constraints. Studies should include TEA and LCA from the earliest stages of research, so emerging concepts are screened for conversion yield, cost, and environmental viability [13]. Concurrently, policy-backed investment in pilot infrastructure is needed to unlock scale-up, while new models of industry-academia co-development can accelerate translation by aligning incentives, sharing risk, and aligning milestones. Finally, success hinges on careful attention to feedstock logistics (ensuring reliable, cost-effective biomass supply) and targeting marketable product streams ideally with multiple value-adding co-products so that biorefineries become economically competitive in real markets, not just academic case studies [14].

References

[1] B. Saha, N. Arshad, M. Sriariyanun, W. Rodiahwati, and M. P. Gundupalli, "Anaerobic digestion: Technology for biogas as a source of renewable energy from biomass—A review," *Applied Science and Engineering Progress*, vol. 18, no. 4, Dec. 2025, doi: 10.14416/j.asep.2025.07.008.

[2] DiMarket. "Charting Industrial Biorefinery Growth: CAGR Projections for 2025–2033." datainsightsmarket.com. Accessed: Oct. 15, 2025. [Online.] Available: https://www.datainsightsmarket.com/reports/industrial-biorefinery-97731

[3] D. Pérez-Almada, Á. Galán-Martín, M. del M. Contreras, and E. Castro, "Integrated techno-economic and environmental assessment of biorefineries: Review and future research directions," *Sustain Energy Fuels*, vol. 7, no. 17, pp. 4031–4050, Aug. 2023, doi: 10.1039/D3SE00405H.

[4] D. C. Makepa and C. H. Chihobo, "Barriers to commercial deployment of biorefineries: A multi-faceted review of obstacles across the innovation chain," *Heliyon*, vol. 10, no. 12, p. e32649, Jun. 2024, doi: 10.1016/J.HELIYON.2024.E32649.

[5] N. M. Kosamia, M. Samavi, K. Piok, and S. K. Rakshit, "Perspectives for scale up of biorefineries using biochemical conversion pathways: Technology status, techno-economic, and sustainable approaches," *Fuel*, vol. 324, p. 124532, Sep. 2022, doi: 10.1016/J.FUEL.2022.124532.

[6] S. Areeya et al., "A review on chemical pretreatment of lignocellulosic biomass for the production of bioproducts: Mechanisms, challenges and applications," *Applied Science and Engineering Progress*, vol. 16, no. 3, 2023, Art. no. 6767, doi: 10.14416/j.asep.2022.02.009.

[7] U.S. Department of Energy. "Systems Development & Integration – Scale-Up Portfolio." energy.gov. Accessed: Oct. 16, 2025. [Online.] Available: https://www.energy.gov/eere/bioenergy/systems-development-integration-scale-portfolio

[8] D. Jose, N. Kitiborwornkul, M. Sriariyanun, and K. Keerthi, "A review on chemical pretreatment methods of lignocellulosic biomass: Recent advances and progress," *Applied Science and Engineering Progress*, vol. 15, no. 4, 2022, Art. no. 6210, doi: 10.14416/j.asep.2022.08.001.

[9] T. Ruensodsai and M. Sriariyanun, "Sustainable development and progress of lignocellulose conversion to platform chemicals," *The Journal of King Mongkut's University of Technology North Bangkok*, vol. 32, no. 4, Mar. 2022, doi: 10.14416/J.KMUTNB.2022.03.001.

[10] A. E. K. Afedzi et al., "Enhancing economic and environmental sustainability in lignocellulosic bioethanol production: Key factors, innovative technologies, policy frameworks, and social considerations," *Sustainability*, vol. 17, no. 2, p. 499, Jan. 2025, doi: 10.3390/SU17020499.

[11] D. Jose, K. Rattanaporn, N. Kittiborwornkul, A. A. Adediran, and M. Sriariyanun, "Biorefining Processes for Valorization of Lignocellulosic Biomass for Sustainable Production of Value-Added Products," in *Lignocellulosic Biomass Refining for Second Generation Biofuel Production*, Florida: CRC Press, 2023, pp. 23–62, doi: 10.1201/9781003203452-2.

[12] A. I. Osman et al., "Life cycle assessment and techno-economic analysis of sustainable bioenergy production: A review," *Environmental Chemistry Letters*, vol. 22, no. 3, pp. 1115–1154, Jun. 2024, doi: 10.1007/S10311-023-01694-Z/FIGURES/4.

[13] N. Arshad et al., "Deep eutectic solvents (DESs) in lignocellulosic biomass pretreatment: Mechanisms and process optimization," *Bioresource Technology Reports*, vol. 31, p. 102190, 2025, doi: 10.1016/j.biteb.2025.102190.

[14] S. Areeya et al., "A review of sugarcane biorefinery: From waste to value-added products," *Applied Science and Engineering Progress*, vol. 17, no. 3, 2024, Art. no. 7402, doi: 10.14416/j.asep.2024.06.004.

Dr. Diana Jose

Dr. Nida Arshad

Prof. Ir. Ts. Dr. Pau-Loke Show
Editor