Bioengineering the Circular Economy: From Biological Resources to Regenerative Production Systems

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Abstract

Linear production systems convert concentrated natural resources into products while dispersing substantial material value as waste, emissions, and low-grade residues. A circular bioeconomy seeks to alter this trajectory by combining renewable biological resources with cascading use, resource recovery, industrial biotechnology, and regenerative production. Yet substituting biomass for fossil feedstocks does not itself establish sustainability. This editorial argues that circular bioengineering must integrate biological conversion with process engineering, industrial ecology, lifecycle assessment, logistics, end-of-life design, and economic feasibility. Current progress in integrated biorefineries, microbial and enzymatic conversion, waste-derived feedstocks, bio-based materials, and industrial symbiosis demonstrates considerable potential, but persistent constraints include feedstock variability, land and water pressures, downstream-processing burdens, scale-up, product quality, infrastructure requirements, and uncertain environmental trade-offs. Research should prioritize waste- and residue-based feedstocks, cascading resource use, scalable conversion platforms, material recovery, demonstrator-scale validation, lifecycle assessment, and techno-economic analysis. The scientific standard for circular bioengineering should therefore be regenerative system performance rather than biological origin alone.

Keywords: circular bioeconomy; biorefinery; industrial biotechnology; resource recovery; waste valorisation; lifecycle assessment; regenerative production

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1.0 Introduction

1.1 Context and Problem Framing

Linear industrial systems have historically been organized around extraction, conversion, consumption, and disposal. This structure has enabled large increases in material productivity, but it also externalizes losses through landfill, combustion, diffuse emissions, wastewater, and low-value residues. Circular-economy scholarship therefore calls for strategies that retain materials and functions at higher value for longer, while reducing dependence on virgin resource extraction (Geissdoerfer et al., 2017; Kirchherr et al., 2017). For biological resources, the challenge is more complex because biomass is renewable only within ecological limits. The bioeconomy encompasses competing visions of biotechnology, biomass utilization, and ecological transformation, and those visions differ substantially in how they treat resource constraints and sustainability (Bugge et al., 2016; D'Amato et al., 2017). A circular bioeconomy must consequently be understood as an integration problem rather than a feedstock substitution strategy. Related circularity scholarship also emphasizes that circular strategies require changes in product design, business models, and system organization rather than waste management alone (Bocken et al., 2016; Ghisellini et al., 2016).

Bioengineering provides important tools for this transition. Microorganisms, enzymes, engineered cells, and integrated biorefineries can convert lignocellulose, agricultural residues, food-processing by-products, organic municipal streams, and industrial side-streams into fuels, chemicals, polymers, proteins, and functional materials. The biorefinery concept seeks to reproduce some of the integration advantages of petroleum refineries while using biomass as a diversified feedstock (Cherubini, 2010). More recent circular-bioeconomy frameworks extend this logic by emphasizing cascading use, waste mining, recovery, and repeated circulation of material value rather than a single conversion step (Mohan et al., 2016; Stegmann et al., 2020). These approaches are increasingly relevant as industries search for lower-carbon and less waste-intensive production routes. Global bioeconomy strategies likewise depend on biotechnology, sustainable biomass governance, and cross-sector coordination rather than feedstock substitution in isolation (El-Chichakli et al., 2016; Carus & Dammer, 2018).

1.2 Why the Issue Matters

The central tension is that biological origin is frequently treated as a proxy for environmental benefit. That assumption is scientifically weak. Biomass cultivation can compete for land, water, nutrients, and food production; conversion can require substantial heat, electricity, chemicals, and separation energy; and biodegradable or bio-based products may still create burdens if their end-of-life pathways are poorly designed. Reviews of biorefinery lifecycle assessment show that environmental results depend strongly on feedstock, allocation, system boundaries, energy systems, and assumptions about co-products (Liu et al., 2021; Gaffey et al., 2024). The editorial position advanced here is therefore that circular bioengineering should be evaluated at the level of integrated production systems. Renewable carbon becomes meaningful only when biological conversion, resource efficiency, industrial integration, recovery pathways, economics, and lifecycle impacts collectively support regenerative production.

2.0 Current Landscape

2.1 Bio-Based Production

Modern biorefineries combine mechanical, chemical, thermochemical, enzymatic, and microbial operations to fractionate biomass and convert its components into multiple products. Integrated concepts seek to allocate carbohydrates, lignin, proteins, lipids, minerals, and process residues to the highest feasible value rather than optimizing a single product in isolation. Kamm and Kamm (2004) framed biorefineries around integrated material and energy conversion, while later analyses have positioned them as core platforms of circular bioeconomy because multiple product streams can improve both resource efficiency and economic resilience (Ubando et al., 2020). This integration is especially important when low-value fuels alone cannot support the economics of complex biomass-processing infrastructure.

2.2 Biorefineries

Waste and residue streams have become particularly important because they can reduce direct competition with food crops and provide an alternative to disposal. Food manufacturing residues contain carbohydrates, proteins, lipids, fibres, antioxidants, and other compounds that can be recovered or bioconverted (Mirabella et al., 2014). Agro-industrial residues can support fermentation, enzyme production, organic acids, bioenergy, biomaterials, and platform chemicals, although pretreatment and compositional variability remain substantial constraints (Yaashikaa et al., 2022). Solid-state fermentation provides another route for valorizing agro-industrial by-products with comparatively low water requirements in some applications (Sadh et al., 2018). These technologies illustrate how waste streams can become feedstocks, but they do not by themselves guarantee circularity. Studies of industrial waste fermentation and waste-biorefineries further demonstrate that value creation depends on integrating recovery pathways across multiple residual streams (Koutinas et al., 2014; Nizami et al., 2017; Vea et al., 2018).

2.3 Biological Resource Recovery

Microbial and enzymatic production systems are also broadening the range of feasible products. Metabolic engineering increasingly enables biological routes to chemicals previously derived predominantly from petrochemical processes, while enzyme technologies can reduce reaction severity and improve selectivity. Industrial biotechnology has consequently become an important link between renewable carbon and manufacturing. At the same time, lignocellulosic feedstocks remain difficult because recalcitrant structure requires fractionation and pretreatment that may consume energy and chemicals or generate inhibitory compounds. Reviews of lignocellulosic valorisation emphasize that effective conversion depends on matching pretreatment, hydrolysis, fermentation, and product recovery to feedstock characteristics rather than assuming a universal process train (Arevalo-Gallegos et al., 2017). The convergence of green chemistry and industrial biotechnology has also expanded the portfolio of bio-based chemicals that can be considered for integrated production (Philp et al., 2013).

2.4 Circular Material Flows

Industrial ecology provides a complementary systems perspective. Industrial symbiosis seeks beneficial exchanges of materials, water, energy, and by-products among firms, thereby allowing one process stream to become another process input (Chertow, 2000). In a circular bioeconomy, this logic can connect agricultural production, food processing, wastewater treatment, biorefineries, energy systems, and materials manufacturing. Such networks shift the unit of analysis from an isolated facility to a regional resource system. Their performance, however, depends on logistics, quality specifications, contractual stability, and infrastructure as much as on conversion chemistry.

3.0 Critical Challenges

3.1 Feedstock Variability

Feedstock variability is a first-order engineering problem. Agricultural residues vary by species, season, geography, storage conditions, harvesting practice, moisture content, and contamination. Food and industrial side-streams can change with recipes, product mixes, and cleaning regimes. Biological conversion processes, by contrast, often require comparatively narrow ranges of substrate composition and inhibitor concentration. Variability therefore affects pretreatment requirements, microbial performance, product yields, and quality consistency. Waste-derived feedstocks can also contain pathogens, metals, pesticides, salts, plastics, or other contaminants that constrain downstream applications. Feedstock characterization, blending strategies, robust biocatalysts, and adaptive process control are essential if circular systems are to operate beyond carefully selected laboratory substrates.

Land, water, and energy requirements create a second challenge. A bio-based route can shift rather than eliminate environmental burdens. Dedicated biomass crops may cause indirect land-use effects or intensify irrigation and fertilizer demand, while energy-intensive drying, sterilization, pretreatment, and separation can offset benefits from renewable carbon. Lifecycle studies repeatedly show that system boundaries and background energy systems strongly influence conclusions about biorefineries (Liu et al., 2021). This makes residue and waste feedstocks attractive, but even these require collection, transport, storage, and sometimes substantial conditioning. Biological resources should therefore be treated as constrained materials with opportunity costs, not as inherently benign inputs.

3.2 Conversion Efficiency

Scale-up and downstream processing frequently determine whether promising biology becomes viable manufacturing. Fermentation titres that appear acceptable in small vessels may produce dilute product streams that require large volumes of water and high separation energy. Complex broths can complicate purification, and product specifications for food, materials, chemicals, or pharmaceuticals may demand stringent contaminant control. Sheldon (2017) has emphasized the importance of mass efficiency and process metrics in judging greener chemistry; analogous discipline is needed in bioengineering. A process that converts waste into a valuable molecule but consumes excessive solvents, utilities, or purification materials may simply relocate inefficiency downstream. Circular chemical-process design similarly requires attention to solvent use, separation, recycle, and material efficiency across the complete process (Clark et al., 2016).

3.3 Environmental Trade-Offs

Economics, logistics, and market formation are equally important. Biomass is spatially distributed and often seasonal, creating collection-radius and storage constraints. Centralized facilities gain economies of scale but increase transport burdens; distributed facilities reduce transport but may sacrifice process efficiency. High-value products can improve profitability but may face limited market size, while commodity products must compete with mature fossil-based infrastructure. Pleissner and Lin (2013) showed the breadth of possible biotechnological routes for food waste, yet product choice remains inseparable from market demand and recovery cost. Circular systems also need stable specifications for secondary materials if manufacturers are to substitute them for primary feedstocks. Food-waste biorefinery reviews show that many proposed valorisation pathways remain at laboratory scale and require stronger techno-economic and environmental evidence before industrial claims are justified (Caldeira et al., 2020).

3.4 Scale and Economics

The final challenge is avoiding circularity claims that are purely nominal. Recycling, reuse, or biological sourcing may lower one impact while increasing another. Circular-economy analysis has therefore increasingly distinguished material circulation from actual sustainability outcomes (Korhonen et al., 2018). Repeated processing can consume energy and degrade material quality; biodegradable products may not degrade under realistic disposal conditions; and energy recovery can destroy material value that might have been retained through cascading use. The relevant question is not whether a loop exists, but whether closing that loop reduces total environmental pressure while remaining technically and economically credible.

4.0 Discussion and Priorities

4.1 Integrative Discussion

Circular bioengineering becomes scientifically coherent only when biology is connected to industrial metabolism. A microbial conversion may be highly selective, yet the overall system can remain inefficient if feedstock collection is energy intensive, purification dominates utility use, or residual streams require costly disposal. Conversely, a modest-yield conversion can be attractive when it integrates with existing infrastructure, exploits a problematic residue, generates useful co-products, and enables recovery of water or nutrients. This is why the biorefinery should be assessed as an interconnected portfolio of material and energy pathways rather than a single reaction.

Cascading use offers a useful organizing principle. Biomass should generally be directed first toward applications that preserve structure or function, then toward biochemical conversion, and finally toward energy recovery when higher-value options are exhausted or technically unsuitable. This hierarchy cannot be absolute because markets, contamination, processing burdens, and regional conditions matter, but it encourages explicit consideration of value retention. Industrial symbiosis can reinforce cascading by linking facilities with complementary resource requirements (Chertow, 2000). Waste heat, carbon dioxide, nutrient-rich water, fermentation residues, and side-stream organics may all become system inputs when quality and logistics permit.

Lifecycle and techno-economic assessment are therefore not peripheral validation tools; they are design instruments. Gaffey et al. (2024) show how methodological decisions in biorefinery LCA can change results across feedstock classes, while techno-economic analysis exposes whether process yield, equipment intensity, feedstock cost, and product price support plausible implementation. Environmental and economic evaluations should be iterated during process development rather than applied only after a flowsheet is fixed. The systems objective is regenerative production: lower virgin-resource demand, reduced pollution, economically viable recovery of value, and end-of-life pathways that maintain rather than dissipate material utility.

4.2 Research and Practice Priorities

A first priority is the development of integrated biorefineries that explicitly optimize multiple resource streams. Research should quantify how carbon, water, nutrients, energy, and co-products move across the complete process and should investigate configurations that allocate each fraction to the highest defensible value. Multi-product integration should be supported by process simulation, mass and energy balances, lifecycle assessment, and techno-economic analysis rather than by conceptual flow diagrams alone.

Second, waste-derived and residue-based feedstocks should receive greater emphasis, together with robust pretreatment and conversion strategies for heterogeneous materials. Work on agro-industrial waste already demonstrates substantial product potential (Yaashikaa et al., 2022), but meaningful progress requires long-duration operation with realistic contaminants, seasonal variation, and storage histories. Demonstrator-scale studies should report feedstock specifications and failure modes rather than only maximum laboratory yields.

Third, microbial and enzymatic platforms should be engineered for scalability and resource efficiency. Strain development should be connected to process-relevant stresses such as inhibitors, osmotic changes, substrate heterogeneity, contamination risk, and fluctuating feed composition. Enzyme systems should be assessed for recovery, reuse, stability, and manufacturing burden. Biological optimization should increasingly target system metrics such as titre, productivity, yield, robustness, and separability simultaneously.

Fourth, circular material and product design must incorporate end-of-life pathways at the outset. Bio-based polymers, composites, coatings, and other materials should be designed for repair, recycling, safe biodegradation, or biological recovery under realistic infrastructure conditions. Material circularity should be assessed together with toxicity, durability, functional performance, and the resources required for reprocessing. This would reduce the risk of creating products whose biological origin is attractive but whose use phase and disposal remain linear.

Fifth, industrial symbiosis and regional resource networks deserve demonstrator-scale validation. Studies should identify where exchanges of residues, water, heat, nutrients, or carbon dioxide remain stable across variable operating conditions and market demand. Geographic information, transport requirements, storage, and quality standards should be included. The strongest evidence will come from networks that demonstrate sustained material exchange rather than hypothetical co-location.

Finally, lifecycle and techno-economic assessment should be embedded in research programs from early development through demonstration. Waste-biorefineries in particular require transparent treatment of allocation, avoided burdens, infrastructure, land effects, energy mixes, product displacement, and uncertainty (Liu et al., 2021). Comparative studies should benchmark new processes against realistic incumbent technologies and alternative waste-management routes. Circular bioengineering will advance most rapidly when experimental innovation and system assessment evolve together.

4.3 Implications for the Journal's Scope

Research in sustainable bioengineering should increasingly connect biological novelty with the material systems in which that novelty is expected to operate. Strong contributions will therefore combine microbial, enzymatic, or biochemical innovation with process engineering, resource accounting, environmental assessment, and evidence about circular integration. Studies of biorefineries, waste-derived feedstocks, bio-based materials, industrial symbiosis, biological carbon utilization, and resource recovery are especially valuable when they demonstrate how laboratory performance translates into system-level benefit. Cross-sector roadmaps for the bio-based economy likewise identify scale-up, knowledge transfer, and collaboration among biological and engineering domains as necessary for implementation (Lange et al., 2021).

The journal should also encourage comparative and integrative work. Lifecycle assessment, techno-economic analysis, pilot demonstrations, material-flow studies, and industrial ecology can reveal constraints that are invisible at the level of isolated biological conversion. Negative findings are valuable when they identify why a nominally circular route fails under realistic energy, water, logistics, quality, or market conditions. The scholarly objective is not to privilege biological routes by default, but to establish which biological-engineering configurations genuinely reduce resource pressure while supporting viable regenerative production.

4.4 Conclusion

A circular bioeconomy cannot be built by exchanging fossil carbon for biological carbon while leaving the logic of linear production unchanged. Regenerative systems require deliberate management of feedstocks, conversion efficiency, water and energy demand, co-products, logistics, material recovery, industrial integration, and end-of-life pathways. Biological resources offer unique capabilities because they are renewable, chemically diverse, and amenable to microbial and enzymatic transformation, but those capabilities operate within ecological and industrial constraints.

The next phase of circular bioengineering should therefore move beyond proof that waste or biomass can be converted into useful products. Scientific progress will be demonstrated when integrated systems retain material value, reduce virgin-resource demand, avoid burden shifting, and perform credibly at relevant scales. Biorefineries, industrial biotechnology, and waste-to-value platforms can become important elements of regenerative production, but only when lifecycle and economic evidence supports their claims. Biological origin is a starting condition; sustainable circularity is a system outcome.

5.0 Declarations

5.1 Author Contributions

Prof. Helena Brooks and Dr. Gilbert Hughes contributed to the conceptual development, literature synthesis, critical interpretation, drafting, and revision of the editorial.

5.2 Funding

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5.3 Competing Interests

The authors declare that they have no conflicts of interest or competing interests relevant to this editorial.

5.4 Data Availability

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5.5 AI Use Disclosure

Generative AI was used to support literature organization and language drafting during preparation of this editorial. The authors remain responsible for independently verifying the accuracy of the arguments, citations, references, and final submitted text in accordance with the publisher's policy.

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