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Editorial

Biofuel Production and Processing Technology, 3rd Edition

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Abstract

The rapid growth of the global population and the impending depletion of fossil fuels, currently meeting approximately 80% of the world's power needs, have intensified interest in biofuels derived from renewable biomass. This editorial refers to the Special Issue, "Biofuel Production and Processing Technology, 3rd Edition," which highlights the transition of fermentation-based technologies from isolated processes into integrated, multifunctional biorefinery platforms. The collection includes nine contributions (eight original articles and one review) covering diverse advancements, including: The valorization of industrial intermediates, strategies to improve anaerobic digestion through co-digestion and heat recovery integration, mechanistic insights into syngas fermentation and the development of multi-product microbial systems, emerging frontier technologies, such as biological hydrogen production in depleted oil and gas reservoirs. Collectively, these studies emphasize that the future of sustainable energy relies on system-level optimization, balancing feedstock flexibility, energy integration, and environmental performance within a circular bioeconomy.

Keywords: biofuels; integrated biorefineries; waste valorization; anaerobic digestion; process optimization; circular bioeconomy

Overview

The rapid and constant growth of the world's population is reflected in the simultaneous increase in energy demand. The scientific community predicts that fossil fuel sources, natural gas, oil, and coal, now meeting about 80% of the world's power needs, will be depleted within the next century [1]. Stephens et al. [2] pointed out that the availability of fossil fuels will be guaranteed until 2084, considering a steady population of 9 billion people with an annual economic growth rate of 1.5–3%. The fossil fuel depletion, together with the environmental concerns due to their utilization, are increasing the interest of both the industry and scientific community, focusing attention on biofuels derived from renewable biomass by applying thermochemical (pyrolysis, torrefaction, liquefaction, direct combustion, gasification) and biochemical (anaerobic digestion and fermentation) conversion techniques [3–5].

Due to the importance of the topic, the Special Issue, entitled "Biofuel Production and Processing Technology, 3rd Edition", continues a series dedicated to showcasing advances in biological conversion pathways, process intensification strategies, and technological innovations that support the large-scale deployment of renewable fuels. Building upon the foundations laid by previous editions, this third collection reflects the rapid evolution of biofuel technologies toward increasingly integrated, flexible, and resource-efficient production systems. The contributions gathered here emphasize not only improvements

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in individual fermentation processes but also the broader transformation of biofuel production into interconnected biorefinery platforms capable of valorizing diverse industrial intermediates and waste streams.

The global transition toward sustainable energy systems requires profound changes in how biological resources and industrial residues are converted into fuels [6]. Fermentation-based technologies, long established in the production of bioethanol and biogas, are now expanding into a much broader portfolio that includes syngas fermentation, biological hydrogen production, and multi-product microbial platforms. Rather than isolated conversion steps, these processes are increasingly being developed as interconnected components of integrated biorefineries, in which feedstock flexibility, energy efficiency, and coproduct valorization determine overall sustainability and economic feasibility. This Special Issue addresses these challenges by presenting recent advances that collectively illustrate how biological conversion pathways can be intensified, integrated, and adapted to diverse waste and intermediate streams.

A recurring theme across the contributions is the strategic utilization of industrial intermediates and residues that are already embedded within existing production chains. In wheat wet-milling, for example, A-starch and B-starch milk represent intermediate streams that can be directly routed into fermentation without energy-intensive drying or extensive chemical conditioning. Studies included in this Special Issue demonstrate that, when coupled with optimized enzymatic hydrolysis and simultaneous saccharification and fermentation (SSF), these substrates can yield high ethanol concentrations with starch utilization exceeding 90%. Importantly, cold hydrolysis regimes operating at moderate temperatures significantly reduce thermal demand, water consumption, and chemical usage, translating to meaningful reductions in operational costs and greenhouse gas emissions. Such integrated starch-ethanol concepts enable the co-production of gluten, ethanol, yeast biomass, fusel alcohols, and carbon dioxide, transforming conventional starch factories into multifunctional biorefineries with improved economic resilience.

The importance of process integration is equally evident in anaerobic digestion systems designed for biogas production. Livestock manure, crop residues, food waste, sewage sludge, and agro-industrial by-products each present specific nutritional imbalances and operational challenges when digested individually. Co-digestion strategies, as reported in several contributions, improve nutrient availability, buffering capacity, and microbial diversity, resulting in greater process stability and higher volumetric methane productivity. Continuous stirred-tank reactor studies demonstrate that co-digestion can sustain elevated organic loading rates without accumulation of short-chain fatty acids, even though synergistic increases in specific methane yield are not always observed. From a practical standpoint, volumetric productivity, operational robustness, and predictable performance are often more critical for full-scale plants than marginal improvements in yield alone.

System-level energy integration emerges as another decisive factor influencing sustainability outcomes. Biogas facilities typically operate combined heat and power units, producing both electricity and thermal energy. However, when installations are in rural or remote areas, full utilization of the generated heat remains challenging. Several studies highlight that unused thermal energy represents a major source of efficiency loss, suggesting that future facility design must more explicitly integrate local heat demands, greenhouse heating, district heating, or process heat for adjacent industries. Consequently, optimizing anaerobic digestion cannot be limited to biological performance but must also encompass heat recovery strategies, internal electricity consumption, and logistical aspects of substrate supply and digestate utilization.

Pretreatment of complex biomass remains a central technical challenge in both bioethanol and biogas production. Lignocellulosic residues, spent coffee grounds, and mez-

cal agave bagasse exemplify feedstocks with high organic content but limited biodegradability due to structural recalcitrance. Chemical oxidation, acid hydrolysis, alkaline treatment, and steam pretreatment can enhance the solubilization of organic matter and increase the availability of fermentable sugars. However, contributions in this Special Issue demonstrate that increased solubilization does not automatically translate into proportional increases in biogas or ethanol yields. In some cases, excessive pretreatment leads to inhibitory compounds or unnecessary energy expenditure, reducing net process efficiency. These findings emphasize that pretreatment strategies must be carefully optimized for each feedstock, with evaluation criteria extending beyond chemical conversion toward net energy recovery, microbial accessibility, and downstream process compatibility.

Beyond substrate-focused optimization, several studies highlight the importance of understanding microbial energy metabolism and regulatory mechanisms. In syngas fermentation using acetogenic bacteria such as *Clostridium ljungdahlii*, fermentation pH exerts a profound influence on proton motive force, ATP synthesis efficiency, and redox balance, ultimately controlling growth rates and ethanol productivity. Mechanistic investigations reveal that improved performance at lower pH is not necessarily associated with higher enzyme expression but rather with enhanced bioenergetic efficiency. Such insights are critical for rational scale-up of gas fermentation platforms, particularly for applications involving industrial off-gases, steel mill exhaust, or biomass-derived syngas, where stable operation under fluctuating gas compositions remains a major engineering challenge.

The exploration of multi-product microbial systems further expands the scope of fermentation-based energy platforms. Glucose-adapted strains of *Enterobacter cloacae* capable of simultaneously producing hydrogen, ethanol, and butanediol demonstrate that metabolic adaptation and natural pH evolution can outperform strictly controlled fermentation strategies. These findings suggest that simplified operational approaches, reduced chemical inputs, and lower process complexity may be achievable without sacrificing productivity. Such developments are particularly relevant for decentralized or small-scale bioprocessing applications, where capital and operational simplicity are key determinants of feasibility.

At the most ambitious end of the technological spectrum, this Special Issue also addresses the emerging concept of biological hydrogen production in depleted oil and gas reservoirs. By stimulating indigenous microbial consortia to convert residual hydrocarbons into hydrogen, these subsurface systems offer the possibility of repurposing fossil infrastructure while integrating carbon management strategies. However, major scientific and engineering uncertainties remain, including low intrinsic hydrogen yields, microbial competition from methanogens and homoacetogens, gas inhibition effects, and long-term reservoir integrity. Furthermore, reliable real-time monitoring of microbial activity and gas composition in heterogeneous subsurface environments remains technically challenging. While the concept holds transformative potential, its practical realization will require close integration of microbiology, reservoir engineering, geochemistry, and advanced sensing technologies.

Taken together, the contributions to this Special Issue underscore that fermentation-based bioenergy systems are undergoing a transition from single-pathway technologies toward multifunctional, integrated production networks. The classical metrics of yield and productivity remain important, but they must now be considered alongside feedstock flexibility, coproduct valorization, energy integration, and environmental performance. In this context, fermentation becomes not only a biological conversion step but a system-level optimization challenge involving complex interactions between microbial metabolism, reactor design, energy flows, and supply chain logistics.

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Looking forward, several research priorities emerge from the collective findings of this Special Issue. First, a deeper mechanistic understanding of microbial energy conservation and stress adaptation is essential for developing more robust and predictable fermentation platforms. Second, advanced monitoring and digital control systems will be required to manage increasingly variable feedstock streams and dynamic operating conditions, particularly in decentralized or waste-based biorefineries. Third, techno-economic and life-cycle assessments must be more tightly integrated with experimental research to guide realistic scale-up strategies and investment decisions. Finally, regulatory frameworks and incentive structures should evolve to recognize the multifunctional environmental benefits of integrated biorefineries, including waste reduction, nutrient recycling, and local energy resilience.

By bringing together studies spanning bioethanol, biogas, syngas fermentation, hydrogen production, and multi-biofuel systems, this Special Issue aimed to provide a comprehensive perspective on the evolving role of fermentation in sustainable energy systems. The diversity of feedstocks, organisms, and process configurations reflects both the complexity and the adaptability of biological conversion technologies.

The insights derived from the studies collected will stimulate further interdisciplinary collaboration and support the development of scalable, economically viable, and environmentally sound bioprocesses that contribute meaningfully to the global transition toward a circular bioeconomy.

Conflicts of Interest: The authors declare no conflicts of interest.

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