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*Editorial*

# Advances in Industrial Biotechnology: Bioprocess and Bioseparation

**Filipe Smith Buarque *, Ailton Cesar Lemes * and Maria Alice Zarur Coelho ***

Department of Biochemical Engineering, School of Chemistry, Federal University of Rio de Janeiro, Rio de Janeiro 21949-900, Brazil

* Correspondence: filipesmith@eq.ufrj.br (F.S.B.); ailtonlemes@eq.ufrj.br (A.C.L.); alice@eq.ufrj.br (M.A.Z.C.)

Biotechnology has emerged as a transformative force in industrial processes, driving sustainable innovations across multiple sectors, including healthcare, food, biofuels, chemicals, and agriculture. Over the past decades, advancements in genetic engineering, metabolic engineering, protein engineering, and bioprocess optimization have positioned modern biotechnology as an indispensable tool for enhancing the yield, efficiency, and economic viability of high-value-added compounds [1,2]. However, for bioproducts to reach industrial-scale production with economic feasibility, the efficiency of bioseparation processes must be continuously improved. Bioseparation, a crucial stage in downstream processing, directly impacts product purity, recovery rates, and overall manufacturing costs [3]. The integration of advanced bioprocessing and bioseparation strategies has therefore become a focal point for both industrial and academic research, aiming to develop more sustainable and economically viable approaches to large-scale bioproduct manufacturing.

## 1. The Role of Bioseparation in Industrial Biotechnology

Bioseparation techniques play a fundamental role in purifying biomolecules, ensuring the quality and functionality of bioproducts. Recent technological breakthroughs, such as ultrafiltration and nanofiltration membranes, have revolutionized protein, enzyme, and biomolecule separation, allowing for higher selectivity, increased recovery rates, and reduced energy consumption [4,5]. Among these innovations, aqueous two-phase extraction (ATPS) has gained prominence due to its efficiency in biomolecule purification, scalability, and eco-friendly characteristics. By eliminating the need for organic solvents, ATPS aligns with global sustainability goals and provides an economically viable alternative for industrial applications [6].

Another significant advancement in bioseparation involves the development of novel chromatographic supports and tailored ligands that enhance specificity in molecular interactions. These improvements contribute to refining separation techniques, reducing processing times, and increasing yields. Additionally, biofunctionalized materials have proven to be highly effective in improving biotechnological product recovery, offering new possibilities for sustainable and efficient bioprocessing. The integration of nanotechnology and biomimetic materials has also enhanced the selectivity and efficiency of bioseparation processes, enabling the separation of complex biomolecules with greater precision and reduced operational costs [7,8].

## 2. Sustainability in Bioprocessing and the Circular Economy

The growing emphasis on sustainability has led to the development of innovative bioseparation strategies aimed at minimizing environmental impact. Traditional solvent-based bioprocesses are being replaced with greener alternatives that prioritize solvent-free

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operations, agro-industrial waste valorization, and the reduction in water and energy consumption. Circular economy principles are increasingly integrated into biotechnological research and development, ensuring that industrial biotechnology aligns with sustainable production models. The use of renewable feedstocks, waste reutilization strategies, and energy-efficient bioprocessing are becoming key priorities for industry leaders and researchers alike. Furthermore, process intensification approaches, such as integrated bioprocessing and in situ product recovery, are gaining traction as methods to enhance efficiency while reducing waste and operational costs [9,10].

This Special Issue highlights new opportunities and challenges for the advancement of circular economy performance assessment, with a focus on technological advances in efficient bioseparation and bioprocess methods. The contributions of each article published in this issue are listed below.

1. Taki, H.; Mine, K.; Matsuo, S.; Kumagai, K.; Matsuyama, H. Simple and economical downstream process development for edible oil production from oleaginous yeast Lipomyces starkeyi. *Processes* **2023**, *11*, 1458.
2. Xia, D.; Gu, P.; Chen, Z.; Chen, L.; Wei, G.; Wang, Z.; Zhang, Y. Control mechanism of microbial degradation on the physical properties of a coal reservoir. *Processes* **2023**, *11*, 1347.
3. Lemes, A.C.; Gautério, G.V.; Rosa, C.A.D.; Brandelli, A.; Kalil, S.J. Two-step purification and partial characterization of keratinolytic proteases from feather meal bioconversion by Bacillus sp. P45. *Processes* **2023**, *11*, 803.
4. Lima, A.G.; Dantas, L.A.; Egea, M.B. Mannitol-based media and static pH are efficient conditions for red pigment production from Monascus purpureus ATCC 36928 in submerged culture. *Processes* **2023**, *11*, 633.
5. Zhong, F.; Ouyang, L.; Deng, N.; Yin, F.; He, J.; Lei, D.; Zhou, H. Determination of 7 Kinds of Alkaloids in Semen Nelumbinis and Its Products by HPLC. *Processes* **2022**, *10*, 2678.
6. Syromyatnikov, M.Y.; Nesterova, E.Y.; Gladkikh, M.I.; Tolkacheva, A.A.; Bondareva, O.V.; Syrov, V.M.; Popov, V.N. High-Throughput Sequencing as a Tool for the Quality Control of Microbial Bioformulations for Agriculture. *Processes* **2022**, *10*, 2243.

Contribution 1 conducted a study of a downstream solid–liquid filtration process for the production of edible oil from the yeast *Lipomyces starkeyi*. The energy consumption and processing cost of the new process were calculated to be 26% and 34% of the conventional method, respectively, suggesting that the new process is promising for industrial use. This new process, capable of continuous operation and efficient in terms of energy consumption and oil production costs, will contribute significantly to the practical use of edible palm oil substitutes for the realization of an eco-friendly bioeconomy.

Contribution 2 addressed the effect of microbial methane production on the physical properties of a coal reservoir. It was reported that microorganisms secrete extracellular enzymes to break down covalent bonds and functional groups of macromolecules in coal and eventually produce methane, which will change its physical properties by altering the pore structure and reducing the fractal dimension of the surface. These changes in properties increased reservoir diffusion and improved coal reservoir pore connectivity, which provides a further scientific basis for the development of coalbed methane.

Contribution 3 aimed to partially purify and characterize a keratinolytic protease produced by *Bacillus* sp. P45 through the bioconversion of feather meal. ATPS with high capacities resulted in purer protease extract without compromising purity and yields, reaching a purification factor of up to 2.6-fold and 6.7-fold in the first and second ATPS, respectively. The results of this study are useful for future studies on scaling up ATPS for enzyme purification and the application of protease in different industrial processes.

Contribution 4 optimized the production of red pigment from *Monascus* sp., in which it was demonstrated that mannitol was efficient as a carbon source both in the production of *Monascus* biomass and in the production of extracellular red pigment. Furthermore, the same concentration of red pigment reported in other studies was identified in a shorter time using mannitol as the sole carbon source and controlled cultivation in a bioreactor.

Contribution 5 established a method for the simultaneous determination of alkaloids in *Semen Nelumbinis* and its by-products using High-Performance Liquid Chromatography (HPLC), a method that is simple, sensitive, accurate, and reproducible. Therefore, the method can be used to determine the content of seven types of alkaloids, which will provide a theoretical basis for the comprehensive evaluation of the quality of *Semen Nelumbinis* and their by-products.

Contribution 6 showed that high-throughput sequencing can be an effective tool for quality and safety control of microbial bioformulations. The analysis based on high-throughput sequencing made it possible not only to confirm the composition indicated on the packaging of the bioformulations but also to reveal the presence of taxa not declared by the manufacturers in the samples, in which only 10% of the bioformulations fully corresponded to the composition. A comparative analysis of the results of the classic microbiological method and the high-throughput sequencing method showed similar results for 80% of the bioformulations studied. However, unlike classical microbiological methods, high-throughput sequencing made it possible to assess the complete bacterial composition of the bioformulations. Finally, it was indicated that high-throughput sequencing can be an effective tool for the quality and safety control of bioformulations.

## 3. Persistent Challenges and Future Directions

Despite remarkable progress, several challenges remain in industrial biotechnology and bioseparation. The efficiency of certain separation techniques is still suboptimal, leading to high operational costs and complex purification steps. The recovery of fragile biomolecules, which are often sensitive to temperature and chemical environments, requires the continuous development of milder and more selective separation methodologies. Additionally, there is a pressing need for standardization in industrial bioseparation protocols to facilitate large-scale implementation and ensure reproducibility across different applications.

Future research must focus on developing advanced, selective, and cost-effective bioseparation techniques that can seamlessly integrate into industrial workflows. Computational tools, such as artificial intelligence and machine learning, are poised to play a crucial role in optimizing bioprocesses by predicting optimal separation parameters, enhancing process efficiency, and reducing waste. The use of digital information and automation in bioseparation can also lead to significant improvements in process monitoring and control. Moreover, improvements in bioreactor design and continuous processing systems will be essential to achieving higher productivity and operational sustainability. The advancement of single-use bioreactors and modular biomanufacturing platforms represents a promising step toward flexible, scalable, and cost-efficient bioproduction.

## 4. The Importance of This Special Issue

This Special Issue brings together cutting-edge research on industrial biotechnology, bioseparation advancements, and sustainable bioprocessing solutions. The articles featured in this issue explore novel purification methodologies, process integration strategies, and biotechnological applications in emerging industries. By addressing critical gaps in knowl-

edge and highlighting innovative approaches, this collection aims to provide meaningful perspectives for researchers, industry professionals, and policymakers seeking to advance biotechnological solutions.

Recent progress in bioprocessing and bioseparation has significantly strengthened industrial biotechnology, fostering the production of sustainable and efficient bioproducts. However, persistent challenges underscore the need for ongoing innovation in cost reduction, process efficiency, and environmental sustainability. This editorial serves as a call to action for the scientific and industrial community to continue pushing the boundaries of biotechnological research, ensuring that biotechnology remains a cornerstone of industrial innovation, economic development, and global sustainability.

By fostering interdisciplinary collaboration, leveraging emerging technologies, and prioritizing sustainability, the future of industrial biotechnology holds immense promise. The integration of biotechnology with advanced materials science, bioinformatics, and process engineering will play a vital role in shaping the next generation of bioseparation technologies. We hope that the contributions in this Special Issue will inspire further research and development in bioseparation and bioprocessing, paving the way for a more efficient, sustainable, and economically viable biotechnological landscape.

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## References

1. Ranjha, M.; Shafique, B.; Khalid, W.; Nadeem, H.R.; Mueen-Ud-Din, G.; Khalid, M.Z. Applications of Biotechnology in Food and Agriculture: A Mini-Review. *Proc. Natl. Acad. Sci. India Sect. B* **2022**, *92*, 11–15. [CrossRef]
2. Ashcroft, E.; Munoz-Munoz, J. A review of the principles and biotechnological applications of glycoside hydrolases from extreme environments. *Int. J. Biol. Macromol.* **2024**, *259*, 129227. [CrossRef] [PubMed]
3. Shanu, K.; Choudhary, S.; Kumari, S.; Anu, K.; Devi, S. Downstream Processing for Bio-product Recovery and Purification. In *Recent Advances in Bioprocess Engineering and Bioreactor Design*; Dhagat, S., Jujjavarapu, S.E., Sampath Kumar, N.S., Mahapatra, C., Eds.; Springer Nature: Singapore, 2024; pp. 139–169.
4. Kammakakam, I.; Lai, Z. Next-generation ultrafiltration membranes: A review of material design, properties, recent progress, and challenges. *Chemosphere* **2023**, *316*, 137669. [CrossRef] [PubMed]
5. Yadav, D.; Hazarika, S.; Ingole, P.G. Recent development in nanofiltration (NF) membranes and their diversified applications. *Emergent Mater.* **2022**, *5*, 1311–1328. [CrossRef]
6. Buarque, F.S.; Gautério, G.V.; Coelho, M.A.Z.; Lemes, A.C.; Ribeiro, B.D. Aqueous Two-Phase Systems Based on Ionic Liquids and Deep Eutectic Solvents as a Tool for the Recovery of Non-Protein Bioactive Compounds—A Review. *Processes* **2023**, *11*, 31–33.
7. Ciulla, M.G.; Massironi, A.; Sugni, M.; Ensign, M.A.; Marzorati, S.; Forouharshad, M. Recent Advances in the Development of Biomimetic Materials. *Gels* **2023**, *9*, 833. [CrossRef] [PubMed]
8. Gebeshuber, I.C. Biomimetic Nanotechnology Vol. 3. *Biomimetics* **2023**, *8*, 102. [CrossRef] [PubMed]

9. Dennison, M.S.; Kumar, M.B.; Jebabalan, S.K. Realization of circular economy principles in manufacturing: Obstacles, advancements, and routes to achieve a sustainable industry transformation. *Discov. Sustain.* **2024**, *5*, 438. [CrossRef]
10. Cahyadi, E.R.; Hidayati, N.; Zahra, N.; Arif, C. Integrating Circular Economy Principles into Agri-Food Supply Chain Management: A Systematic Literature Review. *Sustainability* **2024**, *16*, 7165. [CrossRef]

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