applied sciences

MDPI

Editorial

Bioprocessing and Fermentation Technology for Biomass Conversion

Adeline A. J. Wall [1], Harifara Rabemanolontsoa [1,*] and Joachim Venus [2]

1 International Advanced Energy Science Research and Education Center, Graduate School of Energy Science, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan; wall.adeline.3k@kyoto-u.ac.jp
2 Leibniz Institute for Agricultural Engineering and Bioeconomy, Max-Eyth-Allee 100, 14469 Potsdam, Germany; jvenus@atb-potsdam.de
* Correspondence: rabemanolontsoa.harifara.5c@kyoto-u.ac.jp; Tel.: +81-75-753-9125

In an era where concerns about climate change intersect with the global energy crisis, there is a growing emphasis on alternative resources. To address the problems associated with traditional manufacturing processes using fossil fuels, there is an increasing interest in sustainable methods based on renewables [1].

Biomass is defined as any organic material derived from plants and animals. It is an abundant renewable resource and encompasses a wide range of feedstocks, including agricultural residues and forest waste [2], algae [3–5], cyanobacteria [6–8], and even food-industry-related or municipal solid wastes [9,10]. However, effectively harnessing the energy within this diverse resource poses significant challenges. Traditional combustion methods are not only inefficient but also produce harmful emissions, exacerbating the climate crisis.

Bioprocessing and fermentation technologies offer sustainable and clean alternatives [11], with a carbon-neutral process offsetting the carbon dioxide released during combustion with the carbon dioxide absorbed through plant growth. This closed carbon cycle makes biomass a crucial component of efforts to provide alternatives to fossil fuels, minimize waste, reduce greenhouse gas emissions, combat climate change, and promote sustainability and energy security. These methods operate via the production of value-added products in a proficient, clean, and cost-effective manner, contributing to more sustainable economic growth and an environmentally conscious society [9,12,13].

In particular, converting organic waste such as agricultural residues (e.g., corn stover, wheat straw), forestry litters (e.g., wood chips, sawdust), and various industrial and food wastes [10,14,15] into valuable products helps to reduce the environmental impact of waste disposal and facilitate nutrient recycling. Biomass can be transformed into a range of valuable products, including biofuels, biogas, chemicals, bio-based materials, and even biopharmaceuticals [2,4,6–9,16,17]. This adaptability enables the efficient utilization of biomass across diverse industries.

At the core of this technology are microorganisms, such as bacteria, yeast, and fungi, as well as their enzymes harnessed to convert biomass [15,18]. Bioprocessing typically involves breaking down complex organic molecules into simpler compounds for the production of value-added products [19]. This process mirrors the natural recycling system, making it a compelling choice for a greener future. Recent advancements in bioprocessing and fermentation technology, along with related fields like metabolic and genome engineering, have enhanced economic viability [16,20]. Continuous research and development have led to more efficient engineered microorganisms [21], improved renewable feedstock sources, optimized fermentation processes [14], and the innovation of bioreactor designs [5]. These improvements can lower production costs, increase product yields, and expand the scope of biomass conversion applications. (Bio-)process analytical techniques (Bio-PAT) play a crucial role in the development of precise fermentation processes. It involves the

Citation: Wall, A.A.J.; Rabemanolontsoa, H.; Venus, J. Bioprocessing and Fermentation Technology for Biomass Conversion. *Appl. Sci.* **2024**, *14*, 5. https://doi.org/10.3390/app14010005

Received: 8 December 2023
Accepted: 18 December 2023
Published: 19 December 2023

use of various analytical tools and methods to monitor and control the key parameters of a process in real time. Bio-PAT can assist in improving process understanding, efficiency and ensuring product quality. These tools are valuable in scale-up and scale-down studies where the fermentation process is transferred from the laboratory scale to a larger industrial scale or vice versa. This helps to maintain consistent conditions and ensure reproducibility [22].

However, challenges remain on the path to the widespread adoption of bioprocessing and fermentation technology [23]. Advances in biorefineries reveal technical and economic limitations, including high costs related to feedstock pretreatments, enzymes used in hydrolysis operations, and the recovery and purification of final bioproducts [2,16,24,25]. The upstream and downstream processes involved need improvements to reduce the production costs [4,16]. Furthermore, a deeper understanding of the interactions between enzymes, metabolic pathways, and microorganisms will open up future research interests [18,20].

To achieve carbon neutrality and even negativity, collaborations between governments, industries, and researchers are essential to conduct life cycle assessments (LCAs) that include social, cultural, economic, and operational aspects [1,26]. Partnerships between research institutions and private enterprises with technological innovation could lead to the development of "advanced biorefineries" [11]. For example, multifunctional concepts coupling waste-generating industries with biorefineries could reduce waste disposal costs and generate income through the production of value-added bioproducts [9,24]. Gradually replacing or improving existing industrial processes using bioprocessing methods can also lead to more sustainable, cost-effective, and environmentally friendly outcomes [19,27,28]. With growing public awareness of the environmental impacts and the valorization of waste disposal, the linear economy based on fossil fuels is finding a path to evolve into a circular bioeconomy [26].

In conclusion, bioprocessing and fermentation technology for biomass conversion represent a promising avenue for addressing the urgent challenges of climate change, energy security, and sustainable development [3]. Continued investment, innovation, and collaboration in cross-disciplinary research areas can pave the way towards a more sustainable and eco-friendly future, supporting economic growth while providing alternatives to fossil fuels, minimizing our ecological footprint, and creating wealth.

Author Contributions: Conceptualization, H.R. and A.A.J.W.; validation, H.R., A.A.J.W. and J.V.; formal analysis, A.A.J.W.; investigation, A.A.J.W.; resources, A.A.J.W.; writing—original draft preparation, A.A.J.W.; writing—review and editing, H.R. and J.V.; visualization, H.R.; supervision, H.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

References

1. Zaimes, G.; Vora, N.; Chopra, S.; Landis, A.; Khanna, V. Design of Sustainable Biofuel Processes and Supply Chains: Challenges and Opportunities. *Processes* **2015**, *3*, 634–663. [CrossRef]
2. Zabed, H.; Sahu, J.N.; Suely, A.; Boyce, A.N.; Faruq, G. Bioethanol Production from Renewable Sources: Current Perspectives and Technological Progress. *Renew. Sustain. Energy Rev.* **2017**, *71*, 475–501. [CrossRef]
3. Cheirsilp, B.; Maneechote, W.; Srinuanpan, S.; Angelidaki, I. Microalgae as Tools for Bio-Circular-Green Economy: Zero-Waste Approaches for Sustainable Production and Biorefineries of Microalgal Biomass. *Bioresour. Technol.* **2023**, *387*, 129620. [CrossRef] [PubMed]
4. Kim, S.; Im, H.; Yu, J.; Kim, K.; Kim, M.; Lee, T. Biofuel Production from Euglena: Current Status and Techno-Economic Perspectives. *Bioresour. Technol.* **2023**, *371*, 128582. [CrossRef] [PubMed]
5. Trivedi, J.; Aila, M.; Bangwal, D.P.; Kaul, S.; Garg, M.O. Algae Based Biorefinery—How to Make Sense? *Renew. Sustain. Energy Rev.* **2015**, *47*, 295–307. [CrossRef]
6. Noreña-Caro, D.; Benton, M.G. Cyanobacteria as Photoautotrophic Biofactories of High-Value Chemicals. *J. CO2 Util.* **2018**, *28*, 335–366. [CrossRef]

7. Pekkoh, J.; Duangjan, K.; Phinyo, K.; Kaewkod, T.; Ruangrit, K.; Thurakit, T.; Pumas, C.; Pathom-aree, W.; Cheirsilp, B.; Gu, W.; et al. Turning Waste CO_2 into Value-Added Biorefinery Co-Products Using Cyanobacterium *Leptolyngbya* Sp. KC45 as a Highly Efficient Living Photocatalyst. *Chem. Eng. J.* **2023**, *460*, 141765. [CrossRef]
8. Meixner, K.; Kovalcik, A.; Sykacek, E.; Gruber-Brunhumer, M.; Zeilinger, W.; Markl, K.; Haas, C.; Fritz, I.; Mundigler, N.; Stelzer, F.; et al. Cyanobacteria Biorefinery—Production of Poly(3-Hydroxybutyrate) with Synechocystis Salina and Utilisation of Residual Biomass. *J. Biotechnol.* **2018**, *265*, 46–53. [CrossRef]
9. Althuri, A.; Venkata Mohan, S. Emerging Innovations for Sustainable Production of Bioethanol and Other Mercantile Products from Circular Economy Perspective. *Bioresour. Technol.* **2022**, *363*, 128013. [CrossRef]
10. Marzo-Gago, C.; Unger, P.; Schneider, R.; Venus, J.; Pablo López-Gómez, J. Valorising Pasta Industry Wastes by the Scale up and Integration of Solid-State and Liquid-Submerged Fermentations. *Bioresour. Technol.* **2023**, *391*, 129909. [CrossRef]
11. Dragone, G.; Kerssemakers, A.A.J.; Driessen, J.L.S.P.; Yamakawa, C.K.; Brumano, L.P.; Mussatto, S.I. Innovation and Strategic Orientations for the Development of Advanced Biorefineries. *Bioresour. Technol.* **2020**, *302*, 122847. [CrossRef] [PubMed]
12. Khalili-Garakani, A.; Nezhadfard, M.; Iravaninia, M. Enviro-Economic Investigation of Various Flare Gas Recovery and Utilization Technologies in Upstream and Downstream of Oil and Gas Industries. *J. Clean. Prod.* **2022**, *346*, 131218. [CrossRef]
13. Ramchuran, S.O.; O'Brien, F.; Dube, N.; Ramdas, V. An Overview of Green Processes and Technologies, Biobased Chemicals and Products for Industrial Applications. *Curr. Opin. Green Sustain. Chem.* **2023**, *41*, 100832. [CrossRef]
14. Rabemanolontsoa, H.; Triwahyuni, E.; Takada, M. Consolidated Bioprocessing of Paper Sludge to Acetic Acid by Clostridial Co-Culture. *Bioresour. Technol. Rep.* **2021**, *16*, 100842. [CrossRef]
15. Kawa-Rygielska, J.; Pietrzak, W.; Lennartsson, P.R. High-Efficiency Conversion of Bread Residues to Ethanol and Edible Biomass Using Filamentous Fungi at High Solids Loading: A Biorefinery Approach. *Appl. Sci.* **2022**, *12*, 6405. [CrossRef]
16. Devi, A.; Singh, A.; Bajar, S.; Pant, D.; Din, Z.U. Ethanol from Lignocellulosic Biomass: An in-Depth Analysis of Pre-Treatment Methods, Fermentation Approaches and Detoxification Processes. *J. Environ. Chem. Eng.* **2021**, *9*, 105798. [CrossRef]
17. Singhvi, M.; Kim, B.S. Green Hydrogen Production through Consolidated Bioprocessing of Lignocellulosic Biomass Using Nanobiotechnology Approach. *Bioresour. Technol.* **2022**, *365*, 128108. [CrossRef]
18. Periyasamy, S.; Beula Isabel, J.; Kavitha, S.; Karthik, V.; Mohamed, B.A.; Gizaw, D.G.; Sivashanmugam, P.; Aminabhavi, T.M. Recent Advances in Consolidated Bioprocessing for Conversion of Lignocellulosic Biomass into Bioethanol—A Review. *Chem. Eng. J.* **2023**, *453*, 139783. [CrossRef]
19. Kiefer, D.; Merkel, M.; Lilge, L.; Henkel, M.; Hausmann, R. From Acetate to Bio-Based Products: Underexploited Potential for Industrial Biotechnology. *Trends Biotechnol.* **2021**, *39*, 397–411. [CrossRef]
20. Kumar, R.; Kim, T.H.; Basak, B.; Patil, S.M.; Kim, H.H.; Ahn, Y.; Yadav, K.K.; Cabral-Pinto, M.M.S.; Jeon, B.-H. Emerging Approaches in Lignocellulosic Biomass Pretreatment and Anaerobic Bioprocesses for Sustainable Biofuels Production. *J. Clean. Prod.* **2022**, *333*, 130180. [CrossRef]
21. Agrawal, K.; Nair, L.G.; Chaturvedi, V.; Verma, P. Designing Microbial Cellulases Using Genetic Engineering Approach: A Promising Strategy towards Zero-Waste Cellulosic Biorefinery. *Biocatal. Agric. Biotechnol.* **2023**, *52*, 102830. [CrossRef]
22. Neubauer, P.; Anane, E.; Junne, S.; Cruz Bournazou, M.N. Potential of Integrating Model-Based Design of Experiments Approaches and Process Analytical Technologies for Bioprocess Scale-Down. In *Digital Twins: Applications to the Design and Optimization of Bioprocesses*; Herwig, C., Pörtner, R., Möller, J., Eds.; Advances in Biochemical Engineering/Biotechnology; Springer International Publishing: Cham, Switzerland, 2021; pp. 1–28, ISBN 978-3-030-71656-1.
23. Su, T.; Zhao, D.; Khodadadi, M.; Len, C. Lignocellulosic Biomass for Bioethanol: Recent Advances, Technology Trends, and Barriers to Industrial Development. *Curr. Opin. Green Sustain. Chem.* **2020**, *24*, 56–60. [CrossRef]
24. Melendez, J.R.; Mátyás, B.; Hena, S.; Lowy, D.A.; El Salous, A. Perspectives in the Production of Bioethanol: A Review of Sustainable Methods, Technologies, and Bioprocesses. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112260. [CrossRef]
25. Jambo, S.A.; Abdulla, R.; Mohd Azhar, S.H.; Marbawi, H.; Gansau, J.A.; Ravindra, P. A Review on Third Generation Bioethanol Feedstock. *Renew. Sustain. Energy Rev.* **2016**, *65*, 756–769. [CrossRef]
26. Ahmed, S.F.; Kabir, M.; Mehjabin, A.; Oishi, F.T.Z.; Ahmed, S.; Mannan, S.; Mofijur, M.; Almomani, F.; Badruddin, I.A.; Kamangar, S. Waste Biorefinery to Produce Renewable Energy: Bioconversion Process and Circular Bioeconomy. *Energy Rep.* **2023**, *10*, 3073–3091. [CrossRef]
27. Saini, J.K.; Himanshu; Hemansi; Kaur, A.; Mathur, A. Strategies to Enhance Enzymatic Hydrolysis of Lignocellulosic Biomass for Biorefinery Applications: A Review. *Bioresour. Technol.* **2022**, *360*, 127517. [CrossRef]
28. Scapini, T.; Dalastra, C.; Camargo, A.F.; Kubeneck, S.; Modkovski, T.A.; Júnior, S.L.A.; Treichel, H. Seawater-Based Biorefineries: A Strategy to Reduce the Water Footprint in the Conversion of Lignocellulosic Biomass. *Bioresour. Technol.* **2022**, *344*, 126325. [CrossRef]