Discover Applied Sciences

Brief Communication

Value adding bioconversion of residues and byproducts—a logistics challenge

Andreas Rudi[1] · **Sonja Schönrock**[2] · **Wolfgang Laudensack**[3] · **Frank Schultmann**[1] · **Roland Ulber**[3] · **Dirk Holtmann**[2]

Received: 30 August 2024 / Accepted: 18 October 2024

Abstract
Global developments such as climate change, a growing world population and the depletion of fossil resources make the sustainable use of biogenic resources in chemical production inevitable. This would also provide a final product with a higher added value than just utilizing the raw materials for applications in energy generation. In recent years, many researchers have shown that e.g., grass clippings, carrots and potato peels can be biotechnologically converted into high-value chemicals thereby increasing resource efficiency. A particular challenge, however, is the decentralized production of such biogenic raw materials as well as degradation affecting the composition and quality within short periods of time. Therefore, appropriate logistics concepts must be developed and evaluated to economically valorize biogenic raw materials. Such concepts differ significantly in terms of material utilization for the production of chemicals, composting or energetic valorization. This overview presents relevant examples of the conversion of biogenic residues into chemicals investigating basic logistic concepts and highlighting major challenges along bio-based value chains.

1 Highlights

- Many waste and residual materials can be converted into valuable bioproducts.
- Logistics are essential for profitable conversion routes.
- Techno-economic, environmental and social criteria need to be addressed to solve trade-offs in bio-based value chains.

2 Available biological feedstock for bioconversions

Agriculture, industry and municipalities generate a variety of biogenic waste streams that have not been economically viable for further valorization. With the growing interest in bioeconomy, it is desirable to utilize all waste streams as profitably and sustainably as possible. This is particularly important in view of increasing climate change, global population growth and urbanization. According to the European Commission's updated bioeconomy strategy, EU cities should

---

Andreas Rudi and Sonja Schönrock have been contributed equaly to the manuscript.

✉ Dirk Holtmann, dirk.holtmann@kit.edu | [1]Institute for Industrial Production, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany. [2]Institute of Process Engineering in Life Sciences, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany. [3]Institute of Bioprocess Engineering, University of Kaiserslautern-Landau, Gottlieb-Daimler-Straße 49, 67663 Kaiserslautern, Germany.

Discover Applied Sciences (2024) 6:592 | https://doi.org/10.1007/s42452-024-06286-2

become key hubs for the circular bioeconomy to make use of urban biowaste [1]. Due to the depletion of fossil resources and pressing environmental issues, biogenic raw material, in general, are becoming an increasingly attractive feedstock, not only for the energy sector but also for the chemical industry. Agricultural waste, industrial by-products and even urban wastes contain valuable organic materials that can be extracted or converted into high-value products. Waste or by-products from various bio-sources can be considered abundant, cheap and renewable. These biogenic materials are currently used as substrate in anaerobic digestion to produce biogas or as fertilizer. Large quantities are deposited in landfills resulting in the release of large amounts of CO_2 during decomposition. The information on available quantities of biogenic materials is rather uncertain, but there are fairly reliable estimations both at the global level of total materials and for individual material flows. The amount of organic waste was estimated to be in excess of 13×10^9 tons per year [2]. Organic waste accounts for a third of global food production, with 1×10^9 tons being wasted annually [3]. Three types of organic waste are discussed in more detail below: green waste, carrots and potatoes. One of the largest untapped urban biomass waste streams is green waste [4]. Green waste is heterogeneous lignocellulosic biomass with low lignin content that does not originate from agricultural processes or purposeful cultivation and is therefore mainly generated in urban areas. As an example, more than 120×10^3 tons of green waste are collected annually in the districts of Berlin (Germany) [4]. Carrots are one of the most important crops with a global distribution. More than 4×10^7 million tons are produced worldwide every year. After industrial processing, carrot waste represents up to 50% of the raw material still holding large amounts of valuable compounds in its waste streams [5]. Potatoes are produced with an annual quantity of more than 370×10^6 tons worldwide [6]. Depending on the peeling process, residuals represent 15–40% of the initial potato weight [7].

3 Value-adding bioconversions: an exemplary overview

There are several excellent reviews on (bio)-conversion of different residues and by-products (e.g. agro-industrial, crop-residues and food-processing wastes in general [2, 8–12], green waste [4], sugar beet pulp [13, 14], grape pomace [15], carrots or potato peels and wastes [5, 16]). On the one hand, these review articles or original publications describe in detail a large number of raw material-based production routes. On the other hand, they also depict the pre-treatments or supplements. Table 1 shows examples of feedstocks and products, clearly showing that many products are made from different materials. Further, it highlights the wide variety of potential bio-conversion routes starting at the biogenic raw material. For example, biopolymers such as polyhydroxyalkanoates can be produced with many organisms and on various substrates. In addition, many products can be made from a single feedstock, such as grass clippings.

4 Logistic concepts

It is obvious that many biogenic raw materials are available and a variety of conversion routes have already been developed. However, there are still a number of limitations to value-adding bio-based conversion routes for residues and by-products. Firstly, the processes need to be improved, for example in terms of final product concentrations or carbon yields. Secondly, the scalability of the processes has often not been investigated. Thirdly, seasonal fluctuations in quantities and qualities need to be addressed [41]. However, logistics and transportation must also be taken into account, as the residual materials and by-products often have special properties that need to be considered. Fossil resources are characterized by high energy densities, homogeneous composition, and stable, continuous availability from concentrated deposits. In contrast, renewable resources are spatially distributed and seasonally available, have a heterogeneous composition and typically a high moisture content as well as a low energy density due to elevated oxygen content, which contributes to increased degradability and challenges in conversion efficiency and transportability [42]. Biogenic raw materials are typically sourced from a wide array of locations, including agricultural fields, urban areas, and processing industries. This widespread distribution significantly increases the complexity and cost of logistics and transportation compared to fossil resources. This characteristic is referred to as the Diseconomies of Supply ("the less feedstock, the cheaper the provision"), which contrasts with the Economies of Scale ("the higher the capacity, the cheaper the conversion") achieved when converting biogenic raw materials in large plants [43].

Table 1 Examples of bioconversions from various residues and by-products

Starting material	Applications	Literature
Apple pomace	Bioplastics—a *Pseudomonas* strain has been used for the production of medium chain length polyhydroxyalkanoates	[17]
Apple pomace and peanut shell	Organic acids—a mixed culture has been used for the production of citric acid in a solid-state fermentation process	[18]
Brewers' spent grain	Organic acids—*Lactobacillus delbrueckii* subsp. *lactis* was used in a simultaneous fermentation and saccharification process to produce lactic acid	[19]
Brewers' spent grain	Organics acids—Simultaneous saccharification and fermentation with hydrothermal pretreated BSG has been used for the production of itaconic acids with *Ustilago maydis*	[20]
Brewers' spent grain	Organic acids, ethanol—*Cellulomonas uda* has been used in solid state fermentation under a variety of conditions to switch the product spectrum	[21]
Cassava peels	Bioplastics—Cassava peel hydrolysate was used as a carbon source for polyhydroxyalkanoates with the microalgae *Stigeoclonium* sp.	[22]
Cassava peels	Bioplastics—Cassava peel hydrolysate has been used as a carbon source for the production of polyhydroxyalkanoates by *C. necator*	[23]
Carrots	Acetone-butanol-ethanol (ABE)—Carrot's waste was evaluated as a feedstock for acetone-butanol-ethanol (ABE) fermentation by *Clostridium beijerinckii*	[24]
Grape pomace	Lactic acids—Conversion of grape pomace to lactic acid was achieved using an engineered *Lactiplantibacillus plantarum* strain	[25]
Grape pomace	Bioplastics—Polyhydroxyalkanoates were produced by the conversion of grape pomace with *Tepidimonas taiwanensis*	[26]
Grass clippings	Terpenes—Un-supplemented homogenized grass clippings were used as a growth medium for *C. necator* to produce terpenes	[27]
Grass clippings	Ethanol, lactic acid, itaconic acid and acetone-butanol-ethanol (ABE)—Several organisms (*Saccharomyces cerevisiae, Lactobacillus delbrueckii subsp. lactis, Ustilago maydis and Clostridium acetobutylicum*) are cultured grass clippings with and without additives	[28]
Grass clippings	Enzymes—Peroxidases are isolated from homogenized grass clippings and used in wastewater treatment	[29]
Grass clippings	Electrodes—Carbonized grass clippings and their application as electrodes in microbial electrosynthesis as well as microbial fuel cells were investigated	[30]
Grass clippings	Nanomaterials—Production of cellulose nanomaterials by extracting nanocrystals from grass clippings	[31]
Grass clippings and pruning waste	Bio-stimulant and pesticide—*Trichoderma harzianum* was used in a solid-state fermentation to produce the indole-3-acetic acid conidial spores	[32]
Orange peels	Organic acids—A co-culture of *Aspergillus niger* and *Lactobacillus casei* has been used for the conversion of orange peel into lactic acid	[33]
Orange peels	Organic acids—Un-treated citrus waste was converted to lactic acid by *Bacillus coagulans* under thermophilic conditions	[34]
Potato peels	Bioplastics—Sugar extracted from potato peels has been used in the production of polyhydroxyalkanoates using *Bacillus circulans*	[35]
Potato peels/waste	Organic acids—A supplemented hydrolysed potato processing waste has been used as a medium for *Lactobacillus pentosus* for the production of lactic acid	[36]
Pumpkin peels	Acetone-butanol-ethanol (ABE)—Pumpkin peel was used as a feedstock for acetone-butanol-ethanol (ABE) fermentation by *Clostridium beijerinckii*	[37]
Pumpkin peels	Lipids—Pumpkin peel was used as a substrate for lipid production by the oleaginous yeasts *Rhodosporidiobolus azoricus* and *Cutaneotrichosporon oleaginosum*	[38]
Pumpkin peels/waste	Hydrogen—A mixed culture from an anaerobic sludge plant was used to convert pumpkin waste and several other waste streams into hydrogen	[39]
Sugar beet pulp	Organic acids—In a continuous fermentation of *Bacillus coagulans*, hydrolyzed sugar beet pulp was used as a carbon source to produce lactic acid	[40]

In general, the composition of raw materials, whether lignocellulosic, sugar- and starch-based, oil- and protein-rich, or organic waste, along with their temporal and spatial availability, as well as the quantity, quality, and feedstock price, affects the design of the logistical system. Starting with the provision of feedstock through processes such as harvesting, collection, and conditioning, followed by transshipment, transportation, and storage, the feedstock is converted into various products through the so-called Biomass-to-X (BtX) pathways. The conversion processes, which are biochemical like anaerobic digestion and fermentation or thermochemical like combustion, gasification or pyrolysis, yield energy, biofuels, and/or chemicals to meet specific product demands. In facilities such as biomass CHP (Combined Heat and Power) plants and biogas plants bioenergy (electricity and heat) is generated. In contrast, biorefineries focus on the material valorization, producing high-value chemicals. Integrated biorefinery concepts combine multiple conversion processes to produce a diverse range of products, capitalizing on the principle of Economies of Scope, which posits,"*the broader the product portfolio, the lower the average production costs*" [44].

When designing logistic systems for sustainable bio-based value chains, the tradeoff between increasing transportation costs with higher supply quantities and the lower conversion costs associated with greater capacities must be addressed. This design process may result in structures where biogenic raw materials such as grass clippings are harvested and either processed locally at low transportation costs in decentralized small-scale plants with low capacities or transported over long distances to centralized plants with high capacities. Depending on the configuration of the BtX valorization pathway, the design may result in differentiated structures, such as the decentralized refining of grass clippings via fermentation in the first step, followed by centralized refining via enzymatic hydrolysis in the second step and downstream processing in subsequent steps to obtain products like acids. Such designs benefit from the characteristics of intermediate products, which have a higher energy and value density and are therefore more transportable and storable than the original raw material feedstock [45]. Herein, the main challenge noted by research literature is to maximize the economic impact by minimizing logistic costs whilst increasing the revenue streams of the products [46].

In summary, the appropriate design of logistical systems for bio-based value chains integrates the type of biogenic raw material, its costs and market value for the intermediates and final products, as well as temporal and spatial availability to accurately assess suitable BtX valorization pathways. This requires well-founded decisions regarding technology selection, capacity planning, process and system configuration, and plant siting to ensure the development of bio-based value chains that are economically, environmentally, and socially viable. Advanced multi-method approaches combine Geographic Information Systems (GIS) for estimating biomass potentials with Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) for evaluating valorization pathways with Operations Research (OR) techniques for identifying optimal logistic systems. Whereas GIS models provide the input data such as the spatial potentials of biogenic resources (sources) as well as candidate locations for conversion facilities (sinks), TEA and LCA deliver economic and ecological parameters for the mathematical OR models to optimally link the sources and sinks [47, 48]. In combination with Multi-Criteria Decision Analysis (MCDA) for incorporating social factors such as technological acceptance and green premiums, such multi-method approaches provide a robust toolbox for supporting the complex decision-making process of designing efficient logistical systems for implementing innovative value chains while minimizing ecological impacts and maximizing economic returns and social effects. Figure 1 summarizes the processes and decisions along the biomass value chain and illustrates the challenge to master the tradeoff of designing logistical system.

5 Conclusion

In regard of the global challenges that we are facing, new sustainable value chains need to be established. One possibility is to improve the recycling and utilization of residual materials and by-products of biogenic waste streams. Several processes have been developed in recent years, but they still need to be economically implemented. This requires not only improved process performance, but also integrated value chain concepts. It also means a shift from an all-encompassing centralized production to a bioeconomy which is adjusted to all factors like e.g., biomass, seasonal changes, and especially logistics. Eventually, it is economically, environmentally, and socially worthwhile to implement decentralized plants to convert the waste streams to intermediates and then transport these to centralized plants for further utilization of the intermediates. It is likely more efficient to transport intermediates or end products than residues and by-products while solving the tradeoff between the Diseconomies of Supply and the Economies of Scale. With this comment, we hope to motivate scientists in biotechnology and related fields to collaborate with logistics experts at an early stage of process development and to develop more decentralized production methods. Closer collaboration in the process development would speed up the transfer to real applications.

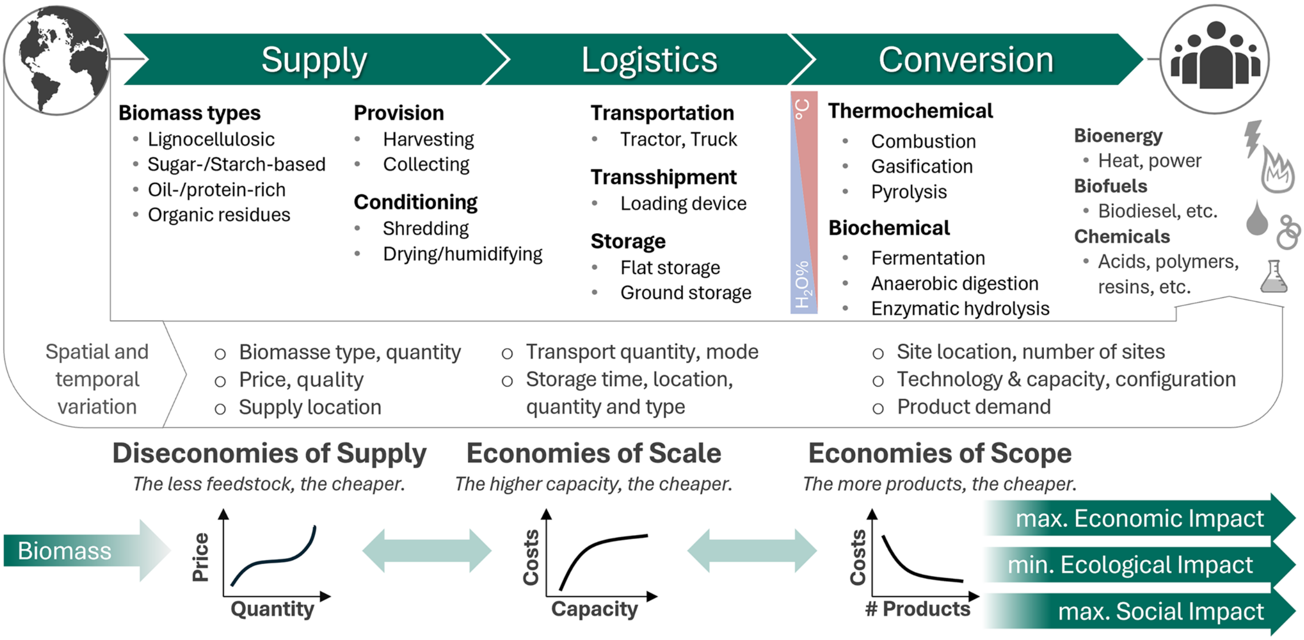

Fig. 1 Processes, decisions and tradeoffs along the bio-based value chain

Author contributions AR, FS, RU and DH: conception of the article, AR, SSch, WL, DH: drafting of the article, final reading and approval of content by all authors.

Funding Open Access funding enabled and organized by Projekt DEAL. This research was prepared within the project "GreenProScale—Prozessintegration und Scale-Up einer Grünschnitt-Bioraffinerie unter Berücksichtigung der Robustheit des Systems" (GreenProScale—Process integration and scale-up of a green waste biorefinery taking into account the robustness of the system), which was funded by the German Federal Ministry of Education and Research (BMBF, grant numbers: 031B1497A and 031B1497B).

Data availability Not applicable.

Declarations

Competing interests The authors declare that they have no conflicts of interest.

References

1. "European Commission, A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment: updated bioeconomy strategy," 2018.
2. Chavan S, Yadav B, Atmakuri A, Tyagi RD, Wong JWC, Drogui P. Bioconversion of organic wastes into value-added products: a review. Bioresour Technol. 2022;344:126398. https://doi.org/10.1016/j.biortech.2021.126398.
3. U. N. E. Programme, " Food Waste Index Report 2024. Think Eat Save: Tracking Progress to Halve Global Food Waste.," 2024.
4. Langsdorf A, Volkmar M, Holtmann D, Ulber R. Material utilization of green waste: a review on potential valorization methods. Bioresour Bioprocess. 2021;8(1):19. https://doi.org/10.1186/s40643-021-00367-5.

5. V. Šeregelj, J. Vulić, G. Ćetković, J. Čanadanovć-Brunet, V. Tumbas Šaponjac, and S. Stajčić, "Chapter 9 - Natural bioactive compounds in carrot waste for food applications and health benefits," in *Studies in Natural Products Chemistry*, vol. 67, R. Atta ur Ed.: Elsevier, 2020, pp. 307–344.
6. Dreyer H. Towards sustainable potato production: partnering to support family farmers in Africa. Potato Res. 2017;60:237–8. https://doi.org/10.1007/s11540-018-9354-7.
7. Barampouti EM, Christofi A, Malamis D, Mai S. A sustainable approach to valorize potato peel waste towards biofuel production. Biomass Convers Biorefinery. 2023;13(9):8197–208. https://doi.org/10.1007/s13399-021-01811-4.
8. Prado-Acebo I, Cubero-Cardoso J, Lu-Chau TA, Eibes G. Integral multi-valorization of agro-industrial wastes: a review. Waste Manag. 2024;183:42–52. https://doi.org/10.1016/j.wasman.2024.05.001.
9. BezirhanArikan E, Canli O, Caro Y, Dufossé L, Dizge N. Production of bio-based pigments from food processing industry by-products (Apple, Pomegranate, Black Carrot, Red Beet Pulps) using Aspergillus carbonarius. J Fungi. 2020;6(4):240. https://doi.org/10.3390/jof6040240.
10. Kaur M, Singh AK, Singh A. Bioconversion of food industry waste to value added products: current technological trends and prospects. Food Biosci. 2023;55:102935. https://doi.org/10.1016/j.fbio.2023.102935.
11. Kamusoko R, Jingura RM, Parawira W, Chikwambi Z. Strategies for valorization of crop residues into biofuels and other value-added products. Biofuels, Bioprod Biorefining. 2021;15(6):1950–64. https://doi.org/10.1002/bbb.2282.
12. Cho EJ, Trinh LTP, Song Y, Lee YG, Bae H-J. Bioconversion of biomass waste into high value chemicals. Bioresour Technol. 2020;298:122386. https://doi.org/10.1016/j.biortech.2019.122386.
13. Puligundla P, Mok C. Valorization of sugar beet pulp through biotechnological approaches: recent developments. Biotechnol Lett. 2021;43(7):1253–63. https://doi.org/10.1007/s10529-021-03146-6.
14. Usmani Z, et al. Valorization of sugar beet pulp to value-added products: a review. Bioresour Technol. 2022;346:126580. https://doi.org/10.1016/j.biortech.2021.126580.
15. Sirohi R, et al. Green processing and biotechnological potential of grape pomace: Current trends and opportunities for sustainable biorefinery. Bioresour Technol. 2020;314:123771. https://doi.org/10.1016/j.biortech.2020.123771.
16. Ebrahimian F, Denayer JFM, Karimi K. Potato peel waste biorefinery for the sustainable production of biofuels, bioplastics, and biosorbents. Bioresour Technol. 2022;360:127609. https://doi.org/10.1016/j.biortech.2022.127609.
17. Pereira JR, et al. Production of medium-chain-length polyhydroxyalkanoates by Pseudomonas chlororaphis subsp. aurantiaca: cultivation on fruit pulp waste and polymer characterization. Int J Biol Macromol. 2021;167:85–92. https://doi.org/10.1016/j.ijbiomac.2020.11.162.
18. Ali SR, Anwar Z, Irshad M, Mukhtar S, Warraich NT. Bio-synthesis of citric acid from single and co-culture-based fermentation technology using agro-wastes. J Radiat Res Appl Sci. 2016;9(1):57–62. https://doi.org/10.1016/j.jrras.2015.09.003.
19. Akermann A, et al. Brewers' spent grain liquor as a feedstock for lactate production with Lactobacillus delbrueckii subsp. lactis. Eng Life Sci. 2020;20(5–6):168–80. https://doi.org/10.1002/elsc.201900143.
20. Weiermüller J, Akermann A, Laudensack W, Chodorski J, Blank LM, Ulber R. Brewers' spent grain as carbon source for itaconate production with engineered Ustilago maydis. Bioresour Technol. 2021;336:125262. https://doi.org/10.1016/j.biortech.2021.125262.
21. Akermann A, Weiermüller J, Chodorski JN, Nestriepke MJ, Baclig MT, Ulber R. Optimization of bioprocesses with Brewers' spent grain and Cellulomonas uda. Eng Life Sci. 2022;22(3–4):132–51. https://doi.org/10.1002/elsc.202100053.
22. Mourão MM, et al. Characterization and biotechnological potential of intracellular polyhydroxybutyrate by Stigeoclonium sp. B23 using cassava peel as carbon source. Polymers. 2021;13(5):687. https://doi.org/10.3390/polym13050687.
23. Vega-Castro O, et al. Characterization and production of a polyhydroxyalkanoate from cassava peel waste: manufacture of biopolymer microfibers by electrospinning. J Polym Environ. 2021;29(1):187–200. https://doi.org/10.1007/s10924-020-01861-1.
24. López-Linares JC, Coca M, Plaza PE, Lucas S, García-Cubero MT. Waste-to-fuel technologies for the bioconversion of carrot discards into biobutanol. Renew Energy. 2023;202:362–9. https://doi.org/10.1016/j.renene.2022.11.093.
25. Shen Y, et al. Production of optical pure L-lactic acid from Cabernet Sauvignon grape pomace by engineered Lactiplantibacillus plantarum. Front Energy Res. 2023;14(11):1228827. https://doi.org/10.3389/fenrg.2023.1228827.
26. Kourilova X, et al. Biotechnological conversion of grape pomace to poly (3-hydroxybutyrate) by moderately thermophilic bacterium Tepidimonas taiwanensis. Bioengineering. 2021;8(10):141. https://doi.org/10.3390/bioengineering8100141.
27. Langsdorf A, Drommershausen A-L, Volkmar M, Ulber R, Holtmann D. Fermentative α-Humulene production from homogenized grass clippings as a growth medium. Molecules. 2022;27(24):8684.
28. Volkmar M, et al. Municipal green waste as substrate for the microbial production of platform chemicals. Bioresour Bioprocess. 2023;10(1):43. https://doi.org/10.1186/s40643-023-00663-2.
29. Langsdorf A, Volkmar M, Ulber R, Hollmann F, Holtmann D. Peroxidases from grass clippings for the removal of phenolic compounds from wastewater. Bioresour Technol Rep. 2023;22:101471. https://doi.org/10.1016/j.biteb.2023.101471.
30. Langsdorf A, et al. Electrodes from carbonized grass clippings for bioelectrochemical systems. Clean Chem Eng. 2024;9:100118. https://doi.org/10.1016/j.clce.2024.100118.
31. Danial WH, Taib RM, Samah MA, Salim RM, Majid ZA. The valorization of municipal grass waste for the extraction of cellulose nanocrystals. RSC Adv. 2020;10(69):42400–7. https://doi.org/10.1039/D0RA07972C.
32. Ghoreishi G, Barrena R, Font X. Using green waste as substrate to produce biostimulant and biopesticide products through solid-state fermentation. Waste Manag. 2023;159:84–92. https://doi.org/10.1016/j.wasman.2023.01.026.
33. Ge XY, Xu Y, Chen X, Zhang LY. Improvement of l-lactic acid production from orange peels in mixed culture system. J Global Biosci. 2014;3(1):354–60.
34. Aulitto M, et al. Thermophilic biocatalysts for one-step conversion of citrus waste into lactic acid. Appl Microbiol Biotechnol. 2024;108(1):155. https://doi.org/10.1007/s00253-023-12904-7.
35. Kag S, Kumar P, Kataria R. Potato peel waste as an economic feedstock for PHA production by Bacillus circulans. Appl Biochem Biotechnol. 2024;196(5):2451–65. https://doi.org/10.1007/s12010-023-04741-1.

36. de Oliveira J, et al. Bioconversion of potato-processing wastes into an industrially-important chemical lactic acid. Bioresour Technol Rep. 2021;15:100698. https://doi.org/10.1016/j.biteb.2021.100698.
37. Tekin N, Köse T, Karatay SE, Dönmez G. Biosorption of Remazol Brilliant Blue R textile dye using Clostridium beijerinckii by biorefinery approach. Environ Sci Pollut Res. 2024;31(39):51568–81. https://doi.org/10.1007/s11356-024-34624-9.
38. Donzella S, et al. Recycling industrial food wastes for lipid production by oleaginous yeasts Rhodosporidiobolus azoricus and Cutaneotrichosporon oleaginosum. Biotechnol Biofuels Bioprod. 2022;15(1):51. https://doi.org/10.1186/s13068-022-02149-3.
39. Ghimire A, et al. Dark fermentation of complex waste biomass for biohydrogen production by pretreated thermophilic anaerobic digestate. J Environ Manag. 2015;152:43–8. https://doi.org/10.1016/j.jenvman.2014.12.049.
40. Alves R, de Oliveira R, Schneider BH, Lunelli CE, Rossell V, Filho RM, Venus J. A simple biorefinery concept to produce 2G-lactic acid from sugar beet pulp (SBP): a high-value target approach to valorize a waste stream. Molecules. 2020;25(9):2113. https://doi.org/10.3390/molecules25092113.
41. Diehlmann F, Zimmer T, Glöser-Chahoud S, Wiens M, Schultmann F. Techno-economic assessment of utilization pathways for rice straw: a simulation-optimization approach. J Clean Prod. 2019;230:1329–43. https://doi.org/10.1016/j.jclepro.2019.04.369.
42. Zimmer T, Rudi A, Müller A-K, Fröhling M, Schultmann F. Modeling the impact of competing utilization paths on biomass-to-liquid (BtL) supply chains. Appl Energy. 2017;208:954–71. https://doi.org/10.1016/j.apenergy.2017.09.056.
43. Rudi A, Müller AK, Fröhling M, Schultmann F. Biomass value chain design: a case study of the upper rhine region. Waste Biomass Valoriz. 2017;8(7):2313–27. https://doi.org/10.1007/s12649-016-9820-x.
44. Petig E, Rudi A, Angenendt E, Schultmann F, Bahrs E. Linking a farm model and a location optimization model for evaluating energetic and material straw valorization pathways—A case study in Baden-Wuerttemberg. GCB Bioenergy. 2019;11(1):304–25. https://doi.org/10.1111/gcbb.12580.
45. Trippe F, Fröhling M, Schultmann F, Stahl R, Henrich E. Techno-economic analysis of fast pyrolysis as a process step within biomass-to-liquid fuel production. Waste Biomass Valoriz. 2010;1(4):415–30. https://doi.org/10.1007/s12649-010-9039-1.
46. Ba BH, Prins C, Prodhon C. Models for optimization and performance evaluation of biomass supply chains: an operations research perspective. Renew Energy. 2016;87:977–89. https://doi.org/10.1016/j.renene.2015.07.045.
47. De Wieuw F, et al. Collection and processing of roadside grass clippings: a supply chain optimization case study for east flanders. Sustainability. 2023;15(18):14006. https://doi.org/10.3390/su151814006.
48. Heck R, Rudi A, Lauth D, Schultmann F. An estimation of biomass potential and location optimization for integrated biorefineries in germany: a combined approach of gis and mathematical modeling. Sustainability. 2024;16(16):6781. https://doi.org/10.3390/su16166781.