Current Research in Microbial Sciences 7 (2024) 100281

Contents lists available at ScienceDirect

Current Research in Microbial Sciences

journal homepage: www.sciencedirect.com/journal/current-research-in-microbial-sciences

Graphing the Green route: Enzymatic hydrolysis in sustainable decomposition

Rajat Singh [a,1], Rajul Jain [b,1], Priyanka Soni [c], Sergio de los Santos-Villalobos [d], Sourav Chattaraj [e], Deblina Roy [f], Debasis Mitra [g,*], Ashish Gaur [a,*]

[a] Department of Biotechnology, Graphic Era (Deemed to be University), Dehradun, 248002, Uttarakhand India
[b] Department of Zoology, Dayalbagh Educational Institute (DEI), Agra, 282005, New Delhi, India
[c] Department of Psychology, Gurukula Kangri (Deemed to be University), Haridwar, Uttarakhand, India
[d] Instituto Tecnológico de Sonora, 5 de febrero 818 sur, 85000, Ciudad Obregón, Sonora, Mexico
[e] Centre for Industrial Biotechnology Research, School of Pharmaceutical Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, 751 003, Odisha, India
[f] Department of Agronomy, Bidhan Chandra Krishi Viswavidyalaya, Nadia, West Bengal, 741252, India
[g] Department of Microbiology, Graphic Era (Deemed to be University), Dehradun, 248002, Uttarakhand India

ABSTRACT

This graphical review article explores how sustainable decomposition contributes to environmental sustainability in waste management with a focus on enzymatic hydrolysis. Methods such as composting and anaerobic digestion efficiently break down organic waste and reduce landfill use and greenhouse gas emissions, while producing valuable resources such as compost and biogas. In particular, enzymatic hydrolysis offers advantages over chemical methods because it operates under mild conditions, targets specific substrates precisely, and yields purer products with fewer side reactions. Its renewable and biodegradable nature aligns with sustainability goals, making it suitable for waste decomposition, biorefining, and resource recovery. Enzymatic waste conversion reduces waste and pollution, conserves natural resources, and supports circular economy. Various ongoing studies have aimed to enhance the efficiency and environmental benefits of enzymatic hydrolysis, enabling innovative waste-to-value solutions that address environmental, economic, and social challenges. This article emphasizes the importance of its timely examination of enzymatic hydrolysis as a prominent method for sustainable waste decomposition, stressing its environmental, economic, and societal benefits. It distinguishes itself through its extensive analysis of chemical methods, its emphasis on the circular economy, and its delineation of future research directions and the need for interdisciplinary collaboration to advance this innovative technology.

Introduction

Sustainable decomposition efficiently manages organic waste and minimizes harm to the environment. It breaks down organic waste and reduces landfill use and greenhouse gas emissions (Yatoo et al., 2024). Composting and anaerobic digestion convert organic waste into useful resources such as compost and biogas. These processes engage communities in waste reduction efforts. Integrating sustainable decomposition into waste management achieves environmental, economic, and social benefits (Sharma et al., 2024). This will build a sustainable future. Hydrolysis can play an important role in waste decomposition and management, offering pathways towards a more sustainable future (Srivastava et al., 2023). Hydrolysis promotes resource recovery, renewable energy generation, and environmental protection by various means (Fig. 1).

Various enzymes substrates are used in enzymatic hydrolysis such as β-Glucosidases which hydrolyze cellobiose into two glucose molecules, Exoglucanases (CBH – Cellobiohydrolases) acts on the ends of the cellulose chains to release cellobiose units, Laccase catalyzes the oxidation of phenolic compounds in lignin, Exopeptidases cleave peptide bonds at the ends of protein chains, either from the amino end (aminopeptidases) or the carboxyl end (carboxypeptidases) (Gonzalez-Gonzalez and Miranda-Lopez, 2022). The enzymatic hydrolysis is the most significant step in modern biotechnology, given green chemistry, researchers has made efforts to develop new strategies for improving enzymatic hydrolysis efficiency. Hydrotropic treatment also improves the reactivity of substrates such as miscanthus and oat hulls and has been shown to notably increase the reducing sugar yields in studies (Denisova et al., 2016). Moreover, chemoenzymatic deracemization of secondary benzylic acetates have been developed with high selectivities and

---

* Corresponding authors.
E-mail addresses: debasismitra3@gmail.com (D. Mitra), gashishdrdo@gmail.com (A. Gaur).
[1] Equal contribution

https://doi.org/10.1016/j.crmicr.2024.100281

conversions in non-conventional media. In addition, its highlight about the significance of enzymatic hydrolysis in biochemical biomass conversion, focusing on its advantages like mild conditions, high sugar yields and specificity which are indispensable for the economic production of fermentable sugars from lignocellulosic biomass (Yuan et al., 2020). Waste recycling using enzymatic hydrolysis is a green and sustainable process in degrading various organic materials. This practice breaks down complex molecules through the use of enzymes, which leads to the degradation of hazardous chemicals within the environment. It was found that enzyme-mediated bioremediation as a cheap and effective technology can be able to sufficiently degrade harmful chemicals within the environment by introduction of genetic engineering and immobilization techniques. Optimization of the reaction media and supporting materials (e.g., using ionic liquids (ILs)) can boost the enzyme functions notably in the recyclable reuse ability, increased reaction rates and better stability especially on lipase-catalyzed (Toshiyuki, 2023).

This graphical review addresses a critical need in the field of environmental sustainability by examining how enzymatic hydrolysis, a specific method of sustainable decomposition, can significantly enhance waste management practices. The urgency to find more efficient and eco-friendly waste treatment solutions stems from increasing global waste production and the detrimental environmental impacts of conventional waste disposal methods, such as landfilling and incineration.

Unmatched advantages of enzymatic hydrolysis against chemical methods

Enzymatic hydrolysis offers unmatched advantages over chemical methods (Amezcua-Allieri et al., 2017, Jain et al., 2023). Enzymes operate under mild conditions, thus minimizing energy consumption and reducing environmental harm (Kleekayai et al., 2024). Enzymes target specific substrates with high precision, resulting in efficient reactions (Barbosa et al., 2019; Yi et al., 2022; Zhang and Zheng, 2022). This reduces the need for extensive purification. Enzymatic hydrolysis yields a higher product purity and minimizes side reactions (Rojo et al., 2023). Enzymes are renewable and biodegradable, and are aligned with sustainability goals. Enzymatic hydrolysis is superior for waste decomposition, biorefining, and sustainable resource recovery (Zaaba and Jaafar, 2020; Chook et al., 2023; Siddiqui, and Dahiya, 2022). In addition, enzymatic hydrolysis often results in purer products with fewer side reactions, thereby improving the overall efficiency (Li et al., 2020; Xin et al., 2024). Finally, enzymes are renewable and biodegradable, aligning with sustainability goals and reducing the impact of waste treatment. Therefore, the efficiency, selectivity, and environmental benefits of enzymatic hydrolysis make it a superior choice for many applications including waste breakdown, biorefining, and sustainable resource recovery (Fig. 2).

Circular economy refers to the process of using waste from one industry as a raw material for another. It is based on the sustainable development principle of "reduce, recycle, reuse, recovery, and restore" which transforms the traditional linear model of the economy (make-use-throw) into a much more efficient circular model. To be more precise, the production of high-value goods through the recycling of bio-waste might be the future solution to realising the goal of a bio-based circular economy (Rojas et al., 2022). Enzymatic waste conversion aligns with these 5Rs of the circular economy by reducing greenhouse gases and landfill waste; recycling waste into useful bioproducts like bioenergy, biopesticide, bioethanol, etc.; maximizing the reuse of different resources; recovering the efficiency of the resources and restoring natural resources. Enzymatic conversion also fosters the economic benefits, and promotes innovation in technology (Chakraborty et al., 2023).

Significant lignocellulosic wastes are produced during the brewing process, including barley straw and brewer's discarded grains. González-García et al. (2018) designed a biorefinery system that used these residues to produce xylooligosaccharides (XOS) and bio-ethanol. The environmental effect was assessed using Life Cycle Assessment (LCA), with an emphasis on mass and energy balances. The five sections of the biorefinery system were fermentation, XOS purification,

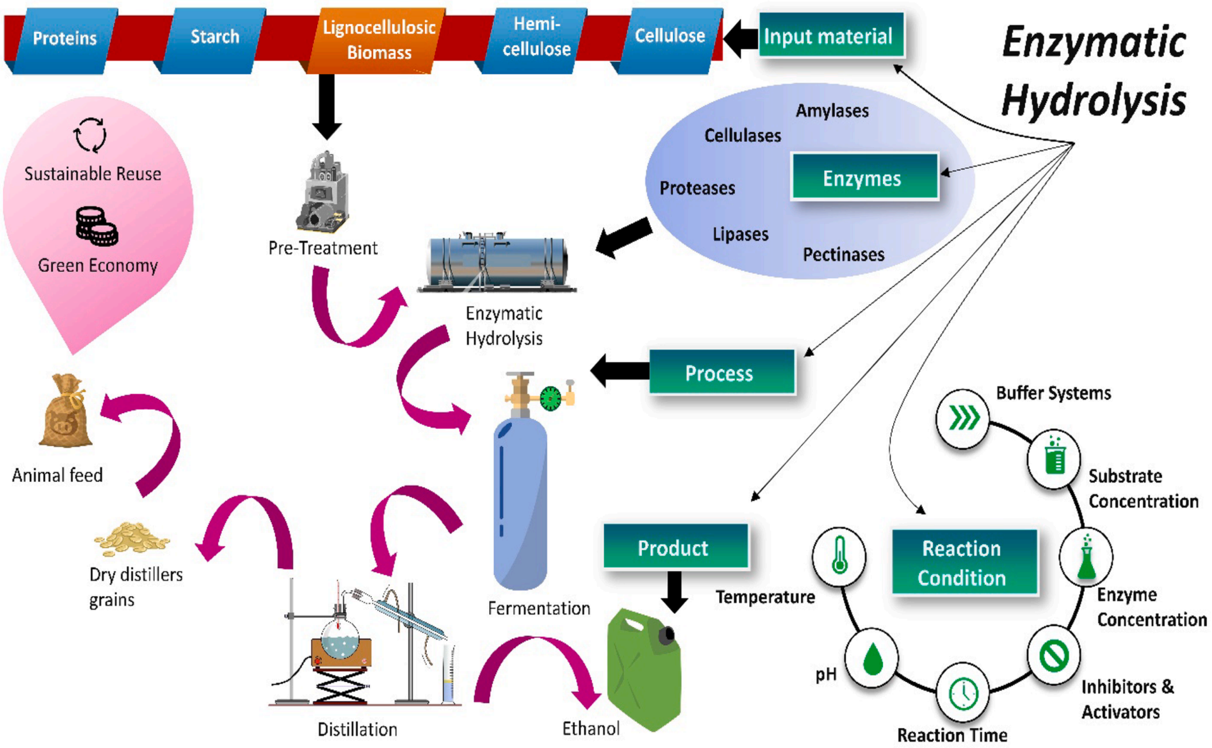

Fig. 1. Enzymatic hydrolysis: pathway to sustainable green economy.

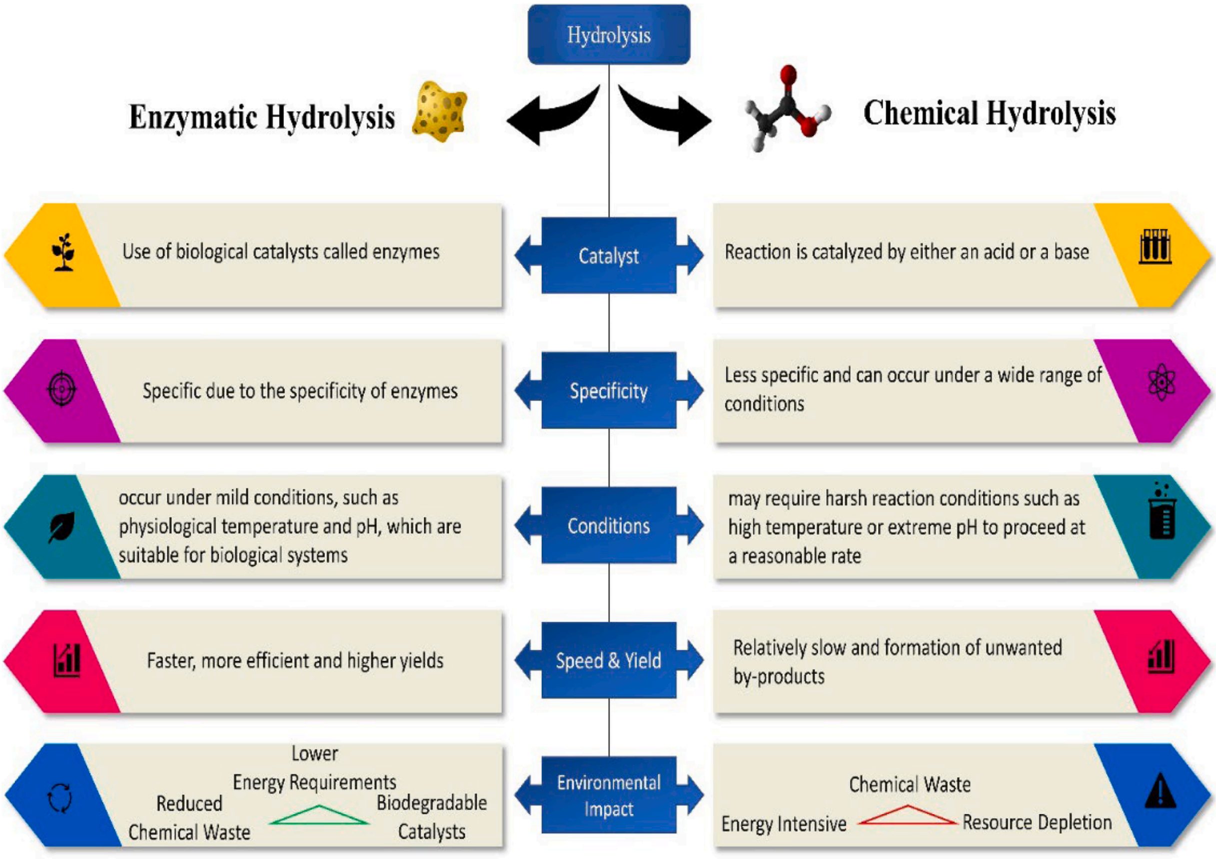

Fig. 2. Advantages with the application of enzymatic hydrolysis over chemical hydrolysis.

autohydrolysis pretreatment, reconditioning/storage, and bio-ethanol purification. Two environmental hotspots were found using LCA: the generation of steam for autohydrolysis and the creation of enzymes for saccharification/fermentation. The environmental effects of heating with wood chips as opposed to natural gas were decreased by 44% to 72%. To preserve non-renewable resources and avoid future material shortages, alternative manufacturing methods that make use of trash are essential. It is feasible to separate biowaste for fermentation. Study conducted by Molina-Peñate et al. (2023) proposed a solid-state fermentation technique to valorize the leftover solids from biowaste following enzymatic hydrolysis. Two anaerobic digestion digestates were tested in a 22 L bioreactor to counteract an acidic pH and promote *Bacillus thuringiensis* growth. The finished product included insecticidal proteins and 4×10^8 spores per gram. This process uses every material from the hydrolysis of biowaste in a sustainable manner.

Enzymatic waste conversion: a path to environmental sustainability

Enzymes convert organic waste into valuable products, thereby reducing landfill waste and pollution (Sharma et al., 2021). They efficiently break down complex compounds under mild conditions, save energy, and minimize harmful by-products (Zahedifar et al., 2021). This method addresses waste management issues and helps conserve natural resources by extracting valuable components. Enzymatic waste conversion supports a circular economy and treats waste as a resource for sustainability (Hawrot-Paw and Stańczuk., 2022). Various ongoing studies have aimed to reduce environmental impacts and create economic opportunities through innovative waste-to-value solutions. The industrial sector for the enzymatic production of biofuels, food and beverages, textiles, and pharmaceuticals is experiencing rapid growth due to the increasing demand for sustainable solutions. Enzymatic hydrolysis is an effective method for converting biomass into biofuels, while enzymes are used to improve product quality sustainably in food processing and textiles. In the pharmaceutical industry, enzymes are used to streamline drug synthesis, reducing costs and environmental impact. Ongoing innovations in enzyme engineering aim to broaden applications and address challenges such as cost and scalability, with continued research focused on sustainable industrial practices (Fig. 3).

Industrial set up, cost analysis and global prospect for using enzymes

Industrial facilities for enzymatic waste treatment, such as bioreactors, are essential for optimizing the efficiency and scalability of enzymatic hydrolysis (Shokrkar et al., 2018). These bioreactors are designed to maintain optimal conditions for enzyme activity, such as controlled temperature, pH, and substrate concentrations. They facilitate both continuous and batch processing of substantial amounts of organic waste, ensuring a consistent and efficient transformation into valuable products (Olivieri et al., 2021). Modern bioreactor designs incorporate automated monitoring and control systems to sustain ideal reaction conditions and improve enzyme stability (Mitra and Murthy, 2022). Additionally, bioreactors can be integrated with downstream processing units to separate and purify the resulting hydrolysate, enhancing the overall efficiency and sustainability of waste treatment. Their adaptability allows for the customization of enzyme mixtures to target specific types of organic waste, expanding the application of enzymatic hydrolysis across various industrial sectors. Therefore, bioreactors play a critical role in implementing enzymatic technologies in large-scale waste management and resource recovery initiatives, contributing to the advancement of a circular economy (Kumar and Verma, 2021).

The enzymes market in waste management is expected to grow due

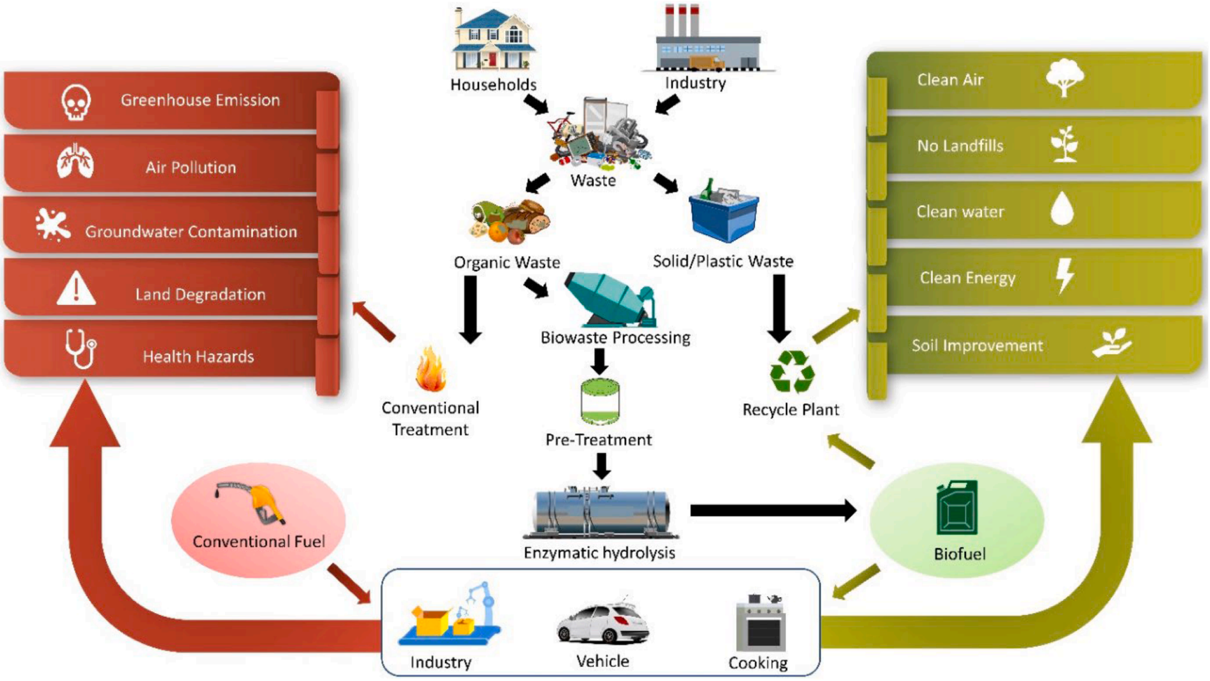

Fig. 3. Enzymatic hydrolysis based waste conversion for sustainable environment.

to rising environmental regulations and a growing focus on sustainability. Enzymatic hydrolysis, which offers benefits over chemical methods, is driving demand for enzymes in biorefining and resource recovery (Bilal et al., 2019). Future forecasts indicate further market expansion as ongoing research enhances enzyme performance, stability, and scalability. This positions enzymatic technologies as crucial to advancing waste treatment practices and supporting circular economy initiatives. Patent US 9388088 B2 introduces methods and formulations designed to process organic waste, extracting valuable nutrients from both plant and animal sources (Jeffrey et al., 2008). The approach utilizes enzymatic treatment under precise conditions to break down the organic material, resulting in a nutrient-rich liquid extract. This patent stands out by focusing on enzymatic digestion specifically for converting fresh organic waste into beneficial forms, distinguishing it from other patents that address different types of waste or disposal techniques. For instance, Patent WO2019168811A1 (Gregg et al., 2019) explores the creation of enzymes capable of breaking down polymers like polyethylene terephthalate (PET), while Patent WO 01/32588 A1 (Pohjola, 1999) discusses the formulation of compost accelerators where enzymes play a critical role. Each patent addresses distinct aspects of waste processing and enzyme applications in their respective fields.

The global market for enzyme sales related to sustainable waste management and decomposition is dominated by several key players, including Novozymes® (combined with Chr. Hansen to become Novonesis), DuPont Industrial Biosciences (now part of IFF), and BASF®. Novozymes leads with a diverse portfolio of enzymes tailored for waste management, biorefining, and other industrial applications (Norus, 2004). DuPont Industrial Biosciences offers innovative enzyme solutions that enhance waste conversion processes and promote sustainability. BASF® focuses on enzymes that improve efficiency in waste treatment and resource recovery. These companies invest heavily in research and development to optimize enzyme performance, stability, and scalability, driving advancements in enzymatic hydrolysis and supporting the transition to a circular economy. Their efforts are crucial in addressing global environmental challenges by providing efficient, sustainable solutions for organic waste decomposition.

Conducting a cost analysis of enzyme-assisted green technology at the technical level involves examining various factors that affect the overall expense and economic feasibility of the process (Climent Barba et al., 2022). Key aspects to consider include the cost of enzyme production, which can be high due to the need for specialized fermentation facilities, raw materials, and purification steps. The stability and reusability of enzymes are also critical, as enzymes that degrade rapidly or cannot be reused frequently increase operational costs (Wiltschi et al., 2020). Optimizing the process is essential to ensure that enzymes function efficiently under industrial conditions, reducing energy consumption and maximizing yield (Singh et al., 2017). The high specificity of enzymes can lower the need for extensive downstream purification, thus potentially reducing costs (Robinson, 2015). However, achieving scalability remains a significant challenge, as efficiencies observed in laboratory settings may not directly translate to industrial-scale operations. Investments in research and development to enhance enzyme performance, along with the integration of enzymatic processes into existing waste management systems, are crucial for cost-effectiveness. While initial expenses may be substantial, long-term benefits such as decreased environmental impact, lower energy requirements, and improved waste conversion rates contribute to the economic viability of enzyme-assisted green technologies (Matsakas et al., 2017).

Challenges and future directions in enzymatic hydrolysis for waste sustainability

There are several challenges in the use of enzymatic hydrolysis for waste sustainability. Optimizing enzymatic reactions to accelerate waste conversion is a major hurdle. Ensuring enzyme stability under different environmental conditions and scalability for industrial use are other concerns. Development of new enzyme systems with broader substrate specificity is necessary to increase the base of enzyme hydrolysis in various fields. Heterogeneity, impurities, acidity, water content in waste particularly fats, oils, and greases (FOG) and high raw material waste, underutilization, increasing by-products are another major challenge. Enzymatic hydrolysis faces challenges due to high enzyme loads (Baena et al., 2022; Zulfigar and Ahmad, 2022). Despite these challenges, the future of enzymatic hydrolysis for waste sustainability appears to be promising. Continued research efforts are aimed at enhancing enzyme performance, exploring novel enzyme sources, and improving process integration for seamless waste treatment. Collaboration among scientists, engineers, and policymakers is required. Future directions include advancing enzyme engineering and optimizing the process parameters. Integrating enzymatic technologies into waste management infrastructure is crucial as it has the potential to revolutionize waste treatment practices. Implementing intensified processing technologies for enzymatic hydrolysis, enzymatic treatment for high-value product conversion and aim for less chemical-intensive pretreatments for sustainability could be the future directions (Vera et al., 2022). Technical challenges with high-solids enzymatic hydrolysis of insoluble lignocellulosic materials appear to be associated with the decreased free water content (da Silva et al., 2020). Enzymatic hydrolysis is a limiting step in the manufacture of biofuels; the practicality of producing biofuels from biomass is limited by the high cost of enzymes, the generation of enzymatic activity inhibitors, and fermentation microorganisms (Pino et al., 2018).

Author contributions

R.G., R.J., P.S., D.R., D.M., A.G. were involved in the manuscript writing, data collection, figures reparation and editing; S.D.L.S.V., S.S., D.M., A.G. were involved in manuscript refinement, supervision and important intellectual content discussion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *[Current Research in Microbial Sciences]* and was not involved in the editorial review or the decision to publish this article.

Data availability

Data will be made available on request.

Acknowledgments

The authors are thankful to Graphic Era (Deemed to be University), India; Siksha ‘O’ Anusandhan (Deemed to be University), India; Instituto Tecnológico de Sonora, Mexico; Dayalbagh Educational Institute (DEI), India; Bidhan Chandra Krishi Viswavidyalaya, India for support and special thanks to Gowri vasanthkumar, Current Research in Microbial Sciences.

References

Amezcua-Allieri, M.A., Sánchez Durán, T., Aburto, J., 2017. Study of chemical and enzymatic hydrolysis of cellulosic material to obtain fermentable sugars. J. Chem. 2017.

Baena, A., Orjuela, A., Rakshit, S.K., Clark, J.H., 2022. Enzymatic hydrolysis of waste fats, oils and greases (FOGs): status, prospective, and process intensification alternatives. Chem. Eng. Process. 175, 108930.

... & Barbosa, M.S., Freire, C.C., Almeida, L.C., Freitas, L.S., Souza, R.L., Pereira, E.B., Soares, C.M., 2019. Optimization of the enzymatic hydrolysis of Moringa oleifera Lam oil using molecular docking analysis for fatty acid specificity. Biotechnol. Appl. Biochem. 66 (5), 823–832.

Bilal, M., Iqbal, H.M., 2019. Sustainable bioconversion of food waste into high-value products by immobilized enzymes to meet bio-economy challenges and opportunities–a review. Food Res. Int. (123), 226–240.

Chakraborty, D., Chatterjee, S., Althuri, A., Palani, S.G., Mohan, S.V., 2023. Sustainable enzymatic treatment of organic waste in a framework of circular economy. Bioresour. Technol. 370, 128487.

Chook, K.Y., Aroua, M.K., Gew, L.T., 2023. Enzyme biocatalysis for sustainability applications in reactors: a systematic review. Ind. Eng. Chem. Res. 62 (28), 10800–10812.

Climent Barba, F., Grasham, O., Puri, D.J., Blacker, A.J., 2022. A simple techno-economic assessment for scaling-up the enzymatic hydrolysis of MSW pulp. Front. Energy Res. 10, 788534.

da Silva, A.S.A., Espinheira, R.P., Teixeira, R.S.S., de Souza, M.F., Ferreira-Leitão, V., Bon, E.P., 2020. Constraints and advances in high-solids enzymatic hydrolysis of lignocellulosic biomass: a critical review. Biotechnol. Biofuels 13, 1–28.

Denisova, M., Makarova, E., Pavlov, I., Budaeva, V., Sakovich, G., 2016. Enzymatic hydrolysis of hydrotropic pulps at different substrate loadings. Appl. Biochem. Biotechnol. 178, 1196–1206. https://doi.org/10.1007/s12010-015-1938-y.

González-García, S., Morales, P.C., Gullón, B., 2018. Estimating the environmental impacts of a brewery waste–based biorefinery: bio-ethanol and xylooligosaccharides joint production case study. Ind. Crops Prod. 123, 331–340.

Gonzalez-Gonzalez, M.R., Miranda-Lopez, R., 2022. Cellulases, hemicellulases and ligninolytic enzymes: mechanism of action, optimal processing conditions and obtaining value-added compounds in plant matrices. MOJ Food Process Technol. 10 (2), 30–37.

Gregg Tyler, B., Christopher, W.J., Bryon, S., Donohoe, N., Rorrer, J.E., Mcgeehan, H.P., Austin, Mark, D.A.. 2019. Enzymes for polymer degradation. Patent Publication of WO2019168811A1 https://patents.google.com/patent/WO2019168811A1/en?oq=WO2019168811A1.

Hawrot-Paw, M., Stańczuk, A., 2022. From waste biomass to cellulosic ethanol by separate hydrolysis and fermentation (SHF) with Trichoderma viride. Sustainability 15 (1), 168.

Jain, R., Gaur, A., Suravajhala, R., Chauhan, U., Pant, M., Tripathi, V., Pant, G., 2023. Microplastic pollution: understanding microbial degradation and strategies for pollutant reduction. Sci. Total Environ., 167098

Jeffrey W. YoungLewis A. Spencer. 2008. Methods and compositions for digestion of organic waste. Patent Publication of US9388088B2. https://patents.google.com/patent/US9388088B2/en.

Kleekayai, T., Singh, U., FitzGerald, R.J., 2024. Optimisation of low temperature (8°C) enzymatic hydrolysis of acid whey using design of experiments (DOE) for the generation of thermally stable whey protein hydrolysates. Food Hydrocoll. 147, 109351.

Kumar, B., Verma, P., 2021. Biomass-based biorefineries: an important architype towards a circular economy. Fuel 288, 119622.

... & Li, H., Chen, X., Xiong, L., Zhang, L., Chen, X., Wang, C., Chen, X., 2020. Production, separation, and characterization of high-purity xylobiose from enzymatic hydrolysis of alkaline oxidation pretreated sugarcane bagasse. Bioresour. Technol. 299, 122625.

Matsakas, L., Gao, Q., Jansson, S., Rova, U., Christakopoulos, P., 2017. Green conversion of municipal solid wastes into fuels and chemicals. Electron. J. Biotechnol. 26, 69–83.

Mitra, S., Murthy, G.S., 2022. Bioreactor control systems in the biopharmaceutical industry: a critical perspective. Syst. Microbiol. Biomanuf. 1–22.

Molina-Peñate, E., del, Carmen, Vargas-García, M., Artola, A., Sánchez, A., 2023. Filling in the gaps in biowaste biorefineries: the use of the solid residue after enzymatic hydrolysis for the production of biopesticides through solid-state fermentation. Waste Manage. 161, 92–103.

Norus, J., 2004. Building regional competencies: the industrial enzymes industry.

Olivieri, G., Wijffels, R.H., Marzocchella, A., Russo, M.E., 2021. Bioreactor and bioprocess design issues in enzymatic hydrolysis of lignocellulosic biomass. Catalysts 11 (6), 680.

Pino, M.S., Rodríguez-Jasso, R.M., Michelin, M., Flores-Gallegos, A.C., Morales-Rodriguez, R., Teixeira, J.A., Ruiz, H.A., 2018. Bioreactor design for enzymatic hydrolysis of biomass under the biorefinery concept. Chem. Eng. J. 347, 119–136.

Pohjola, P. 1999. Compost accelerator mixture, Patent Publication of WO2001032588A1, https://patents.google.com/patent/WO2001032588A1/en?oq=WO+01%2f32588+A1+.

Robinson, P.K., 2015. Enzymes: principles and biotechnological applications. Essays Biochem. 59, 1.

Rojas, L.F., Zapata, P., Ruiz-Tirado, L., 2022. Agro-industrial waste enzymes: perspectives in circular economy. Curr. Opin. Green Sustain. Chem. 34, 100585.

Rojo, E.M., Filipigh, A.A., Bolado, S., 2023. Assisted-enzymatic hydrolysis vs chemical hydrolysis for fractional valorization of microalgae biomass. Process Saf. Environ. Prot. 174, 276–285.

Sharma, P., Gaur, V.K., Sirohi, R., Varjani, S., Kim, S.H., Wong, J.W., 2021. Sustainable processing of food waste for production of bio-based products for circular bioeconomy. Bioresour. Technol. 325, 124684.

Sharma, S., Pappu, A., Asolekar, S.R., 2024. Sustainable recycling of paddy straw through development of short-fiber-reinforced composites: exploring gainful utilization of agricultural waste. Clean Technol. Environ. Policy 26 (1), 109–127.

Shokrkar, H., Ebrahimi, S., Zamani, M., 2018. A review of bioreactor technology used for enzymatic hydrolysis of cellulosic materials. Cellulose, 25, 6279–6304.

Siddiqui, N.M., Dahiya, P., 2022. Enzyme-based biodegradation of toxic environmental pollutants. Development in Wastewater Treatment Research and Processes. Elsevier, pp. 311–333.

Singh, V., Haque, S., Niwas, R., Pasupuleti, M., Tripathi, C.K.M., 2017. Strategies for fermentation medium optimization: an in-depth review. Front. Microbiol. 7, 227613.

Srivastava, R.K., Nedungadi, S.V., Akhtar, N., Sarangi, P.K., Subudhi, S., Shadangi, K.P., Govarthanan, M., 2023. Effective hydrolysis for waste plant biomass impacts sustainable fuel and reduced air pollution generation: a comprehensive review. Sci. Total Environ. 859, 160260.

Toshiyuki, I., 2023. Enzymatic reactions using ionic liquids for green sustainable chemical process; stabilization and activation of lipases. Chem. Record 23. https://doi.org/10.1002/tcr.202200275.

... & Vera, R.E., Zambrano, F., Suarez, A., Pifano, A., Marquez, R., Farrell, M., Gonzalez, R., 2022. Transforming textile wastes into biobased building blocks via enzymatic hydrolysis: a review of key challenges and opportunities. Clean. Circ. Bioecon. 3, 100026.

Wiltschi, B., Cernava, T., Dennig, A., Casas, M.G., Geier, M., Gruber, S., Haberbauer, M., Heidinger, P., Acero, E.H., Kratzer, R., Luley-Goedl, C., 2020. Enzymes revolutionize the bioproduction of value-added compounds: from enzyme discovery to special applications. Biotechnol. Adv. 40, 107520.

Xin, D., Yin, H., Ran, G., 2024. Efficient production of High-Purity manno-oligosaccharides from guar gum by citric acid and enzymatic hydrolysis. Bioresour. Technol., 130719

... & Yatoo, A.M., Hamid, B., Sheikh, T.A., Ali, S., Bhat, S.A., Ramola, S., Kumar, S., 2024. Global perspective of municipal solid waste and landfill leachate: generation, composition, eco-toxicity, and sustainable management strategies. Environ. Sci. Pollut. Res. 1–30.

Yi, Zheng, Zhang, Mingming, Zheng, 2022. Editorial: exploration of highly active enzymes, performance enhancement and enzymatic processing techniques. Front. Bioeng. Biotechnol.

Yuan, B., Debecker, D., Wu, X., Xiao, J., Fei, Q., Turner, N., 2020. One-pot chemoenzymatic deracemisation of secondary alcohols employing variants of galactose oxidase and transfer hydrogenation. ChemCatChem 12. https://doi.org/10.1002/cctc.202001191.

Zaaba, N.F., Jaafar, M., 2020. A review on degradation mechanisms of polylactic acid: hydrolytic, photodegradative, microbial, and enzymatic degradation. Polym. Eng. Sci. 60 (9), 2061–2075.

Zahedifar, P., Pazdur, L., Vande Velde, C.M., Billen, P., 2021. Multistage chemical recycling of polyurethanes and dicarbamates: a glycolysis–hydrolysis demonstration. Sustainability 13 (6), 3583.

Zhang, Y., Zheng, M., 2022. Exploration of highly active enzymes, performance enhancement and enzymatic processing techniques. Front. Bioeng. Biotechnol. 10, 1119604.

Zulfigar, S.B., Ahmad, A.N., 2022. Zero-Waste concept in the seafood industry: enzymatic hydrolysis perspective. Waste Manage. Process. Valor. 207–220.