The Role of Bacteria in Industry and Waste Treatment: Mechanisms, Applications, and Sustainability

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Abstract

This review explores the multifaceted roles of bacteria in industrial biotechnology and waste treatment highlighting their mechanisms, applications and contributions to sustainability. Bacteria with their diverse metabolic capabilities are central to bioprocesses producing valuable compounds like organic acids, biofuels, and bio plastics. in waste treatment they facilitate the removal of pollutants from wastewater through processes like anaerobic digestion and aerobic treatment. The review emphasizes the importance of understanding bacterial metabolism and ecology for optimizing these applications. It discusses bioprocessing, biocatalysis and the use of microbial consortia and biofilm engineering in enhancing efficiency and sustainability. by integrating industrial biotechnology and waste treatment, bacteria contribute to a circular economy where waste is transformed into valuable resources. the review identifies knowledge gaps and suggests paths for the sustainable use of bacteria in both sectors, promoting a more integrated and efficient approach.

Keywords: Waste Treatment, Industrial biotechnology, Bioprocessing

1. Introduction

bacteria permeate all levels of modern life from the microbial communities that impact human health to the biotechnological applications that sustain economic growth and the systems that treat waste [1]. Despite their importance, many misconceptions about bacteria persist. Bacteria, a group of single-celled microorganisms defined by their prokaryotic structure and visible under the light microscope, can be classified into two major divisions: Archaea and Eubacteria [2]. In industrial biotechnology, bacteria are at the heart of bioprocesses producing organic acids, alcohols, solvents, polymers, surfactants, lubricants, biogas through anaerobic degradation of organic matter, and the simultaneous removal of nitrogen and phosphorus from wastewater [3]. Furthermore, many bacterial species are involved in waste treatment, where their roles and mode of action have been widely studied and documented [4]. Industrial biotechnology refers to the use of biological materials and processes to produce any economically beneficial product and waste treatment involves the elimination or separation of various pollutants to valuable resources [5]. The transformation bringing waste into valuable products represents an ideal scenario toward a sustainable circular economy. However, meeting this requirement is not easy. Production of commodity chemicals other than single cell protein and ethanol has not risen as anticipated despite of an urgent call. Wastewater treatment emerges as an alternative sector for sustainable bacterial-related biotechnology offering help in such a two-pronged dilemma of requiring improvement, yet far from saturation [6;7].

2. Fundamentals of Bacterial Metabolism and Ecology

Specifically, bacteria are microorganisms with a cellular structure characterized by prokaryotic organization. They exhibit remarkable diversity, occupying an extensive range of ecological niches [8]. Industrial biotechnology is a discipline that employs living organisms or biochemical processes to produce commercially-valued material. Waste treatment comprises a range of practices applied to wastewater and solid waste to eliminate undesirable components, or alternatively to convert these to forms with commercially-valued end-products [9]. Sustainability refers to a state of development in which use of anthropogenic resources—including raw materials, fossil fuels and energy, and natural ecosystem services—does not exceed replacement rates [10]. With well over a million discrete species (the true number is unknown), bacteria are the most diverse and versatile group of organisms on earth. Such extensive biodiversity has allowed bacteria to colonize a vast array of ecological niches ranging from acid hot springs to frozen tundra, from the deep-sea floor to subterranean geologic formations, and even deep inside metal ores, glass, and petrochemicals [11]. The role of bacteria in industrial biotechnology is emerging as a field of high commercial importance. Public awareness of waste generation and responsible waste management has grown, along with the perception of waste as a potentially reusable resource [1]. The role of Bacteria in industrial biotechnology and waste treatment has been driven by a variety of factors: public awareness of waste generation, growing interest in climate change, and the search for sustainable industrial processes and materials [3]. Wastewater treatment technology, particularly biopurification systems, has become a major industry. Despite these drivers, some industries and interest groups continue to oppose industrial applications of Bacteria. However, popular support for broader use of Bacteria in both industrial biotechnology and waste treatment is likely to strengthen, intensifying demands for evidence-based research on safety and constraints now needed to allow full exploitation of these promising technologies [6;7]

3. Bacteria in Industrial Biotechnology

Industrial biotechnology encompasses microbial production of chemicals, materials, and fuels with applications in the food, feed, agriculture, health, nutrition, packaging, textiles, energy, and environmental sectors [12]. Growth in microbial industrial biotechnology has fostered sustainable advances in science, the principles of which can be readily applied to waste treatment systems. The drivers, metabolic processes, and ecological principles motivating the application of bacteria in industrial biotechnology thus present important parallels with such systems [1].

Biotechnology employs biological resources in a wide range of processes to create value [13]. Industrial biotechnology refers to the application of biotechnology in the production of chemicals and materials on a potentially industrial scale [14]. The industrial biotechnology approach is parallel to waste management processes, where microorganisms are employed to convert unwanted or hazardous substrates into simpler, less harmful, more desirable chemical forms. Bacteria have emerged as key agents in the industrial biotechnology arena for several interrelated reasons [15]. first bacteria have many metabolic capabilities and accompany several generic physiological attributes that make them well suited for the conversion of complex substrates into specific end products. many metabolic pathways are present in various environmental microorganisms [16]. Bacteria can grow quickly achieving high operational cell concentrations, and often avoid strict oxygen requirements. finally bacterial metabolism is highly versatile, making the valorization of commonly available feeds such as sugars or organic acids rather than heartwood or biomass such as lignin or cellulose possible [17].

3.1. Bioprocessing and Fermentation

bacteria are among the oldest living organisms on Earth having first emerged at least 3.48 billion years ago [7] industrial biotechnology employs a range of bacterial species for industrial applications, leveraging the ability of specific strains to convert biomass (such as sugars , starches or organic acids) into commercially valuable products [18] key drivers of industrial applicability include the central role of water and bioprocessing in life on Earth and the emerging dual responsibility of mankind to protect the environment while meeting growing demands for food, fuel, and materials [19]. Bioprocessing also benefits from modularity separate operations can often be mass balanced independently and combined using hard interfaces. Well developed technology exists for screening multiple substrates, overproduction strains and process conditions [20].

Soft robotic grippers based on climbing snail foot (Lepidochitona cinerea) constitute a novel bio-inspiration for an alternative, sustainable, and low-cost grasping tool. These devices exploit the adhesion of small liquid droplets on nanostructured elastomers to grasp and transport delicate objects while remaining controllable via magnetic fields [21].

3.2. Biocatalysis and Enzyme Production

Biocatalysis exploits living cells or their components to drive chemical transformations. Bacterial catalytic activities enable the conversion of a wide range of substrates into a variety of products including chemicals, polymers, biofuels and pharmaceuticals. These compounds can serve directly in industrial and agricultural uses or can provide precursors for further production of high value added chemicals [22]. This technology could provide a significant environmental benefit by minimising aggressive chemical reagents as well as enzyme depletion during reaction and generating biowaste that can be potentially reused. Commercially, this technology is gaining pace to full-scaled application for wastewater treatment, bio-lubricants, bio-surfactants and food additives [23]. The catalysis can be executed through isolated enzymes, whole cells or cell-free extract. Different strategies are adopted during biocatalysis process to augment yield and enhance catalytic turnover through improved substrate binding and product release among many others [24]. Biocatalysis is performed in batch, fed-batch, semi-continuous and continuous processes. For biocatalysis raw substrate materials, biocatalyst-host systems, screening methods and desired product molecule are paramount in determining the feasibility to full-scale application [25].

3.3. Biosurfactants, Biofuels, and Bioplastics

Industrially, bacteria can produce surfactants, fuels, and plastics via fermentation and other microbial processes, with high feasibility and time-to-market [26]. Bacterial biosurfactants can replace synthetic and plant-based surfactants in a variety of applications, remaining commercially competitive in the market. Surfactants fulfil a diverse range of functions in food, textiles, cosmetics, oil recovery, biodiesel production, waste treatment, and pharmaceuticals [27]. Fermentation is economically viable for producing glycerol from renewable raw materials, and certain biofuels (e.g., ethanol, isobutanol, caproic acid, D-limonene) can be produced from a wide range of substrates. Dedicated building blocks for the biorefinery industry can also be generated via fermentation of different organic materials, including amino acids, fatty acids, and organic acids [28]. Bioplastics derived from conventional polymers, such as polylactic acid, polyhydroxy alkanoates, and polyamide 11, can be produced internationally via fermentation, and these materials serve as biodegradable alternatives to fossil-based plastics. Products exhibit a diversity of functionalities, thus fulfilling other commercial demands [29;30].

4. Bacterial Roles in Waste Treatment

wastewater treatment comprises a set of operational configurations designed to remove environmental contaminants from sewage and industrial effluents, significantly improving liquid waste quality before discharge [31] wastewater typically consists of a complex and poorly structured mixture of organic and inorganic substances, capable of sustaining diverse microbial communities. Wastewater contains organic matter (COD) in the form of sugar, starch, fat, protein and other substances, as well as a wide range of inorganic components, including nitrogen, phosphorous and sulphur [32; 33]. Additionally, wastewater poses a secondary threat from live pathogens, such as bacteria, viruses and protozoa pathogenic microorganisms whose preservation within the sludge can trigger high infection rates when the material is reused e.g as fertilizer [6].

Municipal wastewater treatment can be divided into four major processes: pre-treatment, primary treatment, secondary treatment, and tertiary treatment [34]. Pre-treatment consists of mechanical operation forms, such as screening and sedimentation, to remove large debris, oily materials, and sand, which may rapidly and seriously affect following treatment units [35]. Primary treatment aims to settle the solid particles in suspension, leading to separation of high-concentration slurry, which constitutes the primary sludge to be treated. The remaining liquid, effluent, has the quantity of biodegradable organic matter considerably reduced yet still contains around 200 mg COD/L, implying further treatment is necessary [36].

4.1. Sewage and Municipal Wastewater Treatment

Sewage and municipal wastewater treatment constitutes an indispensable process for safeguarding public health and preserving the environment and the diverse species inhabiting it [6]. Despite treatment technologies of long standing, the quest continues to enhance overall system performance and reliability in terms of efficiency, energy consumption, and discharge water quality—especially concerning organic matter, solids, and nutrients. Municipal wastewater comprises a wide variety of readily biodegradable and toxic organic substances, nitrogen, phosphorus, and several trace elements that enter nature through various anthropogenic activities, posing a serious risk to living beings [7]. Waste water treatment encompasses three sequential steps: physical, biological and chemical treatment. In the first step, which consists of either mechanical or physical separation, solid residues, fat and sand materials that may accumulate on pumps and pipes are eliminated as these solid waste materials can disrupt the proper operation of the system [37] After physical separation, biological treatment employing the metabolism of specific microorganisms is applied to remove the bulk of dissolved biodegradable organic material before entering the chemical step [38] See table 1.

Table 1. Overview of Sewage and Municipal Wastewater Treatment Processes

Treatment Stage	Treatment Type	Primary Purpose	Key Components Removed	Main Mechanism	References
Preliminary / Primary Treatment	Physical (Mechanical)	Protect downstream equipment and ensure proper system operation	Large solids, grit, sand, fats, oils, and grease	Screening, grit removal, sedimentation	[37]
Secondary Treatment	Biological	Remove bulk of dissolved and biodegradable organic matter	Biodegradable organic compounds, suspended solids, partial nutrients	Microbial metabolism and biochemical degradation	[38]
Tertiary / Advanced Treatment	Chemical (and/or Physical-Chemical)	Improve effluent quality and protect receiving environments	Nutrients (N, P), residual organics, pathogens, trace contaminants	Chemical precipitation, disinfection, adsorption, filtration	[6], [7]

4.2. Anaerobic Digestion and Biogas Production

Anaerobic digestion is a sequential process that converts organic substrates to biogas in the absence of free oxygen [39]. Biogas is predominantly composed of methane, which can be independently harvested [40]. The digestion process is staged into hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis of complex substrates is the rate-limiting step and requires extracellular enzymes produced by microbes that also ferment dissolved substrates to organic acids, alcohols, carbon dioxide, and hydrogen [41]. These fermentation products are transformed to acetic acid, carbon dioxide, and hydrogen by a second, syntrophic microbial group and finally converted to biogas by methanogens. A complex microbial community operates in concert, forming stable, self-regulating consortia from species adapted to specific substrates and conditions [42].

Biogas has a higher heating value of 28.2 MJ/m3 and produces 17.5 MJ of energy per kg of organic carbon digested. This energy output can meet the world’s energy needs if only agrarian and animal-waste by-products are used [43].

4.3. Aerobic Biological Treatment and Nutrient Removal

Municipal days, wastewater treatment consists of two stages: primary treatment and secondary treatment [44]. The objective of the primary treatment is to improve the quality of raw wastewater to a level that can be treated by physically separating most large solid debris and greases from the wastewater [45]. The removal of BOD during the primary treatment is usually less than 30% [46]. To accomplish this, sewage grid, screening, grit removal, and sedimentation are the typical unit processes. However, the coliform bacteria such as E or fecal coliform still present in the effluent after primary treatment can survive for several days; they can flow to the receiving bodies and cause serious environmental problems and public health concerns [47]. Secondary treatment is designed to remove organic materials, nutrients (N and P), and coliform bacteria. Unlike the primary treatment, it usually employs microorganisms to carry out biochemical transformation mechanism; thus, secondary treatment is often referred as biological treatment. Over 93% of sewage treatment plants utilized biological treatment in the United States [7].

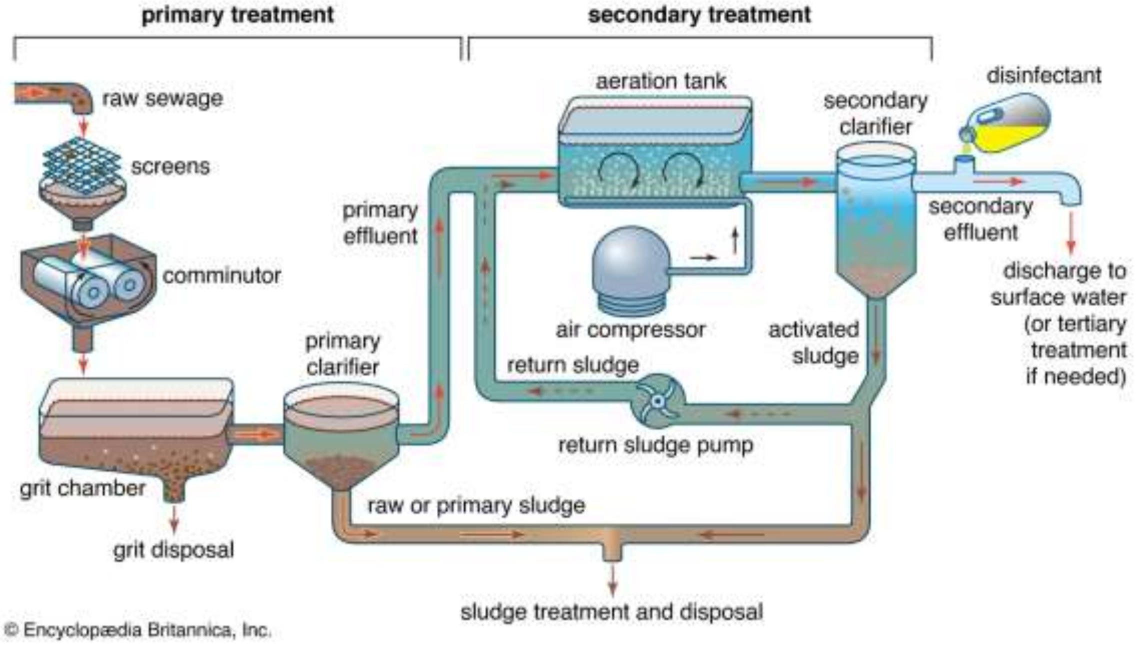

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Figure 1: illustrates wastewater treatment systems.

4.4. Microbial Consortia and Biofilm Engineering

Biological wastewater treatments, usually based exclusively on one or two species or strains of microorganisms, are largely effective but insufficient in critical industrial situations [31]. The supplementing of conventional systems with additional consortia takes advantage of the inherent flexibility, adaptability, and robustness of nature [48]. At any community size larger than two cells, it is impossible to separate competition from cooperation completely [49]. We cannot refer to microbial communities as simple multispecies systems even if competition predominates because toxicity produced by one species or consortium tends to inhibit the rest of the community, eventually leading to a monoculture that disregards the advantages of coexistence [50; 51].

5. Conclusion

In conclusion bacteria are fundamentally important across modern life , playing critical roles in both industrial biotechnology for producing valuable commodities and in waste treatment for environmental remediation. while these two domains have historically been studied in isolation, the increasing global focus on sustainability necessitates an integrated approach. Bacteria with their remarkable metabolic versatility are central to creating a circular economy where waste from one process can serve as feedstock for another. Industrial biotechnology utilizes bacterial capabilities for bioprocessing, biocatalysis and the production of biosurfactants, biofuels and bioplastics. Similarly in waste treatment, bacterial communities drive processes like anaerobic digestion for biogas production and aerobic treatment for nutrient removal. despite the potential, limitations and knowledge gaps remain, underscoring the need for evidence-based research to fully exploit the sustainable applications of bacterial biotechnologies in both industrial production and waste management, ultimately aligning with the principles of a sustainable, cyclical economy.

References:

1. Mfon, E. I. (2024). Microbial biotechnology: application of bacteria in various industrial processes and environment remediation. Int J Dev Sustain Environ Manag, 4(1), 25-33.
2. Grogan, D. W. (2026). Bacterial and archaeal cells. In Cell Physiology Source Book (pp. 85-105). Academic Press.
3. Akoijam, N., Kalita, D., & Joshi, S. R. (2022). Bacteria and their industrial importance. In Industrial Microbiology and Biotechnology (pp. 63-79). Singapore: Springer Singapore.
4. Saini, S., Tewari, S., Dwivedi, J., & Sharma, V. (2023). Biofilm-mediated wastewater treatment: a comprehensive review. Materials Advances, 4(6), 1415-1443.
5. Nielsen J, Tillegreen CB, Petranovic D. Innovation trends in industrial biotechnology. Trends in biotechnology. 2022. cell.com
6. Siles, J. A., & Michán, C. (2019). Bacteria, archae, fungi and viruses: it takes a community to eliminate waste. Microbial Biotechnology, 13(4), 892.
7. Salem, R., ElDyasti, A., & Audette, G. F. (2021). Biomedical applications of biomolecules isolated from methanotrophic bacteria in wastewater treatment systems. Biomolecules, 11(8), 1217.
8. Dey, S., Nayak, A. K., Dhiman, R., Rajaram, H., & Das, S. (2025). Pleomorphism drives the lifestyle transitions in bacteria for micro-niche adaptation in biofilm. Reviews in Environmental Science and Bio/Technology, 1-30.
9. Debroy, A., Joshi, S., Yadav, M., & George, N. (2023). Green synthesis of nanoparticles from bio-waste for potential applications: Current trends, challenges, and prospects. Bio-based materials and waste for energy generation and resource management, 431-466.
10. Cheng, S., Shu, C., Jin, M., & He, Y. (2023). Balancing resources and sustainability: Analyzing the impact of mineral resources utilization on green growth. Resources Policy, 86, 104143.
11. Idigo, M. A., Iheukwumere, I. H., Iheukwumere, C. M., Nwakoby, N. E., & Ike, V. E. (2025). The Role of Insects in the Dissemination of Antibiotic-Resistant Bacteria in the Environment: A Comprehensive Review. Health Science Research International, 1(1), 29-33.
12. Dahiya, D., Sharma, H., Rai, A. K., & Nigam, P. S. (2022). Application of biological systems and processes employing microbes and algae to Reduce, Recycle, Reuse (3Rs) for the sustainability of circular bioeconomy. AIMS microbiology, 8(1), 83.
13. Das, S., Ray, M. K., Panday, D., & Mishra, P. K. (2023). Role of biotechnology in creating sustainable agriculture. PLOS Sustainability and Transformation, 2(7), e0000069.
14. Sokra, I., Somaly, S., & Meta, H. (2026). CRISPR–Cas9–Based genome editing in microbial biotechnology: Advances in metabolic engineering, fermentation systems, and industrial applications. Journal of Agriculture and Technology, 2(1), 154-166.
15. Nag, M., Lahiri, D., Ghosh, S., Sarkar, T., Pati, S., Das, A. P., ... & Ray, R. R. (2024). Application of microorganisms in biotransformation and bioremediation of environmental contaminant: a review. Geomicrobiology Journal, 41(4), 374-391.

16. Choi, K. R., & Lee, S. Y. (2023). Systems metabolic engineering of microorganisms for food and cosmetics production. Nature Reviews Bioengineering, 1(11), 832-857.
17. Bayon-Vicente, G., Toubeau, L., Gilson, M., Gégo, G., Landgey, N., Krings, S., & Leroy, B. (2025). Metabolic pathways to sustainability: review of purple non-sulfur bacteria potential in agri-food waste valorization. Frontiers in Bioengineering and Biotechnology, 13, 1529032.
18. Lips, D. (2021). Practical considerations for delivering on the sustainability promise of fermentation-based biomanufacturing. Emerging Topics in Life Sciences, 5(5), 711-715.20. Pandey K, Pandey M, Kumar V, Aggarwal U, Singhal B. Bioprocessing 4.0 in biomanufacturing: paving the way for sustainable bioeconomy. Systems Microbiology and Biomanufacturing. 2024 Apr;4(2):407-24. researchgate.net
19. Abdulbaqi, A. S., Alsultan, Q. H., Nejrs, S. M., Jassim, S. A., Sulaiman, B. H., Al deen Shawqi, O. S., ... & Khalaf, H. A. (2023). Design and fabrication of bio-inspired robotic systems for developed mobility and functionality in unstructured environments. Khwarizmia, 2023, 46-62.
20. Adrio, J. L., & Demain, A. L. (2014). Microbial enzymes: tools for biotechnological processes. Biomolecules, 4(1), 117-139.
21. Rudel, H. E. (2023). Informing Design of Sustainable Sorbents for Drinking Water Treatment: Faceted Nanohematite for Oxoanion Removal (Doctoral dissertation, Yale University).
22. Lewis, R. D., France, S. P., & Martinez, C. A. (2023). Emerging technologies for biocatalysis in the pharmaceutical industry. ACS Catalysis, 13(8), 5571-5577.
23. Castilla, I. A., Woods, D. F., Reen, F. J., & O'Gara, F. (2018). Harnessing marine biocatalytic reservoirs for green chemistry applications through metagenomic technologies. Marine drugs, 16(7), 227.
24. Dusselier, M., & Lange, J. P. (Eds.). (2022). Biodegradable polymers in the circular plastics economy. John Wiley & Sons.
25. Nagtode, V. S., Cardoza, C., Yasin, H. K. A., Mali, S. N., Tambe, S. M., Roy, P., ... & Pratap, A. P. (2023). Green surfactants (biosurfactants): a petroleum-free substitute for Sustainability─Comparison, applications, market, and future prospects. ACS omega, 8(13), 11674-11699.
26. Nanda, S., Pattnaik, F., Patra, B. R., Kang, K., & Dalai, A. K. (2023). A review of liquid and gaseous biofuels from advanced microbial fermentation processes. Fermentation, 9(9), 813.
27. de Souza, F. M., & Gupta, R. K. (2024). Bacteria for bioplastics: progress, applications, and challenges. ACS omega, 9(8), 8666-8686.
28. Eras-Muñoz, E., Farré, A., Sánchez, A., Font, X., & Gea, T. (2022). Microbial biosurfactants: a review of recent environmental applications. Bioengineered, 13(5), 12365-12391.
29. Chandran, P., Suresh, S., Balasubramain, B., Gangwar, J., Raj, A. S., Aarathy, U. L., ... & Sebastian, J. K. (2025). Biological treatment solutions using bioreactors for environmental contaminants from industrial waste water. Journal of Umm Al-Qura University for Applied Sciences, 11(2), 185-207.
30. Darra, R., Hammad, M. B., Alshamsi, F., Alhammadi, S., Al-Ali, W., Aidan, A., ... & Al-Othman, A. (2023). Wastewater treatment processes and microbial community. In Metagenomics to Bioremediation (pp. 329-355). Academic Press.
31. Wang, K., Yan, D., Chen, X., Xu, Z., Cao, W., & Li, H. (2024). New insight to the enriched microorganisms driven by pollutant concentrations and types for industrial and domestic wastewater via distinguishing the municipal wastewater treatment plants. Environmental Pollution, 361, 124789.

32. Zhang, Z., Liu, W., Gao, Q., Huang, F., Kang, Y., Pan, Y., ... & Gao, S. H. (2023). Microplastics extraction from wastewater treatment plants: Two-step digestion pre-treatment and application. Water Research, 230, 119569.
33. Baksi, S., Saha, D., Saha, S., Sarkar, U., Basu, D., & Kuniyal, J. C. (2023). Pre-treatment of lignocellulosic biomass: review of various physico-chemical and biological methods influencing the extent of biomass depolymerization. International journal of environmental science and technology, 20(12), 13895-13922.
34. Oh, S., Nguyen, H. T., Obayomi, K. S., & Siddiqui, S. I. (2025). Assessing the environmental risk potential of transformation byproducts formed during fungal enzymatic treatment of a pharmaceutical mixture. Journal of Industrial and Engineering Chemistry, 142, 725-735.
35. Tóth, A. J., Fózer, D., Mizsey, P., Varbanov, P. S., & Klemeš, J. J. (2023). Physicochemical methods for process wastewater treatment: powerful tools for circular economy in the chemical industry. Reviews in Chemical Engineering, 39(7), 1123-1151.
36. Awasthi, P., Agrahari, G. K., Patel, A., & Singh, A. (2025). Hybrid membrane technology with renewably derived biological and photocatalytic systems for wastewater treatment. Biodegradation, 36(4), 77.
37. Goswami, R., Chattopadhyay, P., Shome, A., Banerjee, S. N., Chakraborty, A. K., Mathew, A. K., & Chaudhury, S. (2016). An overview of physico-chemical mechanisms of biogas production by microbial communities: a step towards sustainable waste management. 3 Biotech, 6(1), 72.
38. Pagliano, G., Ventorino, V., Panico, A., & Pepe, O. (2017). Integrated systems for biopolymers and bioenergy production from organic waste and by-products: a review of microbial processes. Biotechnology for biofuels, 10(1), 113.
39. Brunecky, R., Li, Y., Decker, S. R., & Himmel, M. E. (2025). Advancing continuous enzymatic hydrolysis for improved biomass saccharification. Biotechnology for Biofuels and Bioproducts, 18(1), 82.
40. Abdelwahed, A. A., Qaisrani, Z. N., Salem, G. E., Ashfaq, M., Pinijsuwan, S., & Abdel-Azeem, A. M. (2025). Ecological and biochemical synergy in Fungal–LAB co-fermentation: From enzymatic priming to sustainable functional foods. Microbial Biosystems, 10(4).
41. Garcia, C. R., Hincapie, M. D. V., Barros, R. M., Córdova, M. E. H., de Castro e Silva, H. L., dos Santos, I. F. S., ... & Pontes, A. J. M. D. O. (2024). Technical–Economic Analyses of Electric Energy Generation by Biogas from Anaerobic Digestion of Sewage Sludge from an Aerobic Reactor with the Addition of Charcoal. Methane, 3(4), 595-616.
42. Khademi, N., Khademi, S., & Harasi, N. J. (2025). Introduction to municipal wastewater treatments. In Municipal Wastewater Treatment (pp. 1-24). Elsevier.
43. Ghimisi, L. (2024). Research on Industrial Wastewater Treatment. Journal of Research & Innovation for Sustainable Society (JRISS), 6(2).
44. Islam, T., Repon, M. R., Islam, T., Sarwar, Z., & Rahman, M. M. (2023). Impact of textile dyes on health and ecosystem: a review of structure, causes, and potential solutions. Environmental Science and Pollution Research, 30(4), 9207-9242.
45. Chen, S., Chen, J., Wang, X., Li, J., Dong, B., & Xu, Z. (2023). Footprints of total coliforms, faecal coliforms and E. coli in a wastewater treatment plant and the probabilistic assessment and reduction of E. coli infection risks. Science of The Total Environment, 900, 165845.

46. Mikiciuk, G., Miller, T., Kisiel, A., Cembrowska-Lech, D., Mikiciuk, M., Łobodzińska, A., & Bokszczanin, K. (2024). Harnessing beneficial microbes for drought tolerance: a review of ecological and agricultural innovations. Agriculture, 14(12), 2228.
47. Kost, C., Patil, K. R., Friedman, J., Garcia, S. L., & Ralser, M. (2023). Metabolic exchanges are ubiquitous in natural microbial communities. Nature Microbiology, 8(12), 2244-2252.
48. Bernstein, H. C., & Carlson, R. P. (2012). Microbial consortia engineering for cellular factories: in vitro to in silico systems. Computational and structural biotechnology journal, 3(4), e201210017.
49. Branduardi, P. (2021). Closing the loop: the power of microbial biotransformations from traditional bioprocesses to biorefineries, and beyond. Microbial Biotechnology, 14(1), 68-73.