17

Postbiotics from Agro-Industrial Waste: Sustainable Bioactive Production for Food and Health Applications

AUTHORS DETAIL

Kiran Khurshid[1], Zubair Azhar Nomi[2], Abdul Mohsin[3], Sadia Mujahid[4], Maira Ashfaq[5] and Baseer Ahmad[2*]

1. College of Animal Sciences and Technology, Yangzhou University, China
2. Faculty of Veterinary and Animal Sciences, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan.
3. Institute of Animal and Dairy Sciences, University of Agriculture, Faisalabad, Pakistan.
4. Department of Human Nutrition and Dietetics, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan.
5. Department of Human Nutrition and Dietetics, Nishtar Medical University, Multan, Pakistan.

*Corresponding author: baseer.ahmad@mnsuam.edu.pk

Received: 12-9-2024 **Revised:** 2-11-2024 **Accepted:** 17-12-2024

Cite this Article as: Khurshid K, Nomi ZA, Mohsin A, Mujahid S, Ashfaq M and Ahmad B, 2024. Postbiotics from Agro-Industrial Waste: Sustainable Bioactive Production for Food and Health Applications. In: Basit A, Khan SA, Muhyuddin S and Mughal MAS (eds), Anim Health Dis Management, Pioneer Page Publishers, Beijing, China, Vol. 2: 165-172. https://doi.org/10.5281/zenodo.17171852

Abstract

Agro-industrial waste is a renewable, rich and cheap substrate that can be used to get non-viable microbial products or metabolic by-products that have health benefits to a host. Microbial fermentation of various wastes like fruit pomace, cereal bran, oil-seed meals, dairy by-products and brewery residues produces these bio actives, which are short-chain fatty acids (SCFA), bacteriocins, exopolysaccharides (EPS), cell wall fragments, peptides, and enzymes. The transformation of such waste to useful postbiotic substances not only offers an environmental solution by mitigating the landfill problem but also offers stable, safe and versatile compounds that can be used in functional foods, animal feed, nutraceuticals, and therapeutic preparations. This chapter sums up the definition and categorization of postbiotics, agro-waste valorization methodology, production technologies, mechanism of action, and application, and challenges and research directions required to commercially use postbiotics.

Keywords: Postbiotics, Agro-Industrial Waste, Sustainable Bioactive Production, Food, Health

1. Introduction

Millions of tons of by-products are produced in the global food industry every year, such as peels of fruits, vegetables, cereal husks, oil seed cakes, dairy processing residues (Lau et al., 2021). Previously regarded as waste, these by-products are a source of rich carbohydrates, protein, lipid, minerals and phytochemicals which can be utilized as substrates in microbial fermentation (Pereira & Vicente, 2010; Mirabella et al., 2014). The transition to the circular models of the bioeconomy focuses on the agro-industrial waste streams being converted into value-added products, i.e., biofuels, bioplastics, organic acids, enzymes and, more recently, postbiotics (Mussatto & Dragone, 2016).

According to the International Scientific Association of Probiotics and Prebiotics (ISAPP), postbiotics is considered to be a preparation of inanimate microorganisms and components that has a health effect on the host (Salminen et al., 2021). Postbiotics do not need to be viable to produce their beneficial effects, unlike probiotics, so they are better preserved during processing and storage, and when traversing the gastrointestinal tract (Żółkiewicz et al., 2020). Lactic acid bacteria, bifidobacteria, and other useful microorganisms that grow on agro-waste foods generate SCFAs, bacteriocins, EPS, bioactive peptides, vitamins, and antioxidant compounds, which are used as postbiotics (Wegh et al., 2019; Moradi et al., 2020). Agro-industrial waste valorization and postbiotic production is beneficial in two ways, firstly, reducing waste disposal challenges on the environment, as well as, the economy and secondly producing high-value products that can find application as functional compounds in the food, pharmaceutical, and animal production industries (Markowiak & Śliżewska, 2018; Cuevas-González et al., 2020).

2. Agro-Industrial Waste as a Substrate for Postbiotic Production

Agro-industrial effluents contain nutrients that are useful in the place of traditional expensive fermentation media (Sadh et al., 2018). An example is fruit pomace which is a source of fermentable sugars and polyphenols; oilseed meals, are sources of proteins and peptides; dairy whey, is a source of lactose and nitrogen; and cereal brans are source of arabinoxylans and β-glucans (Nayak & Bhushan, 2019). The appropriateness of various substrates varies based on the compatibility of the microbial strains, fermentation type (solid-state or submerged) and the desired postbiotic compound (Mussatto & Dragone, 2016).
These wastes when fermented by *Lactobacillus plantarum*, *Lactobacillus rhamnosus* and beyond can be converted to SCFAs, EPS, and bacteriocins with proven antimicrobial, antioxidant and immunomodulatory effects (Zeng et al., 2020; Patel et al., 2021). The more recent researches have perfected the pre-treatment of the substrate (enzymatic hydrolysis, steam explosion) to increase the bioavailability of nutrients in fermentation (Pereira & Vicente, 2010; Wang et al., 2025). Postbiotics have different categories depending on their source and type as presented in Table 1.

Table 1: Classification of Postbiotics and Their Sources

Postbiotic Type	**Description**	**Source/Substrate**
Short-Chain Fatty Acids	Fatty acids with fewer than six carbon atoms	Fruit pomace, dairy by-products
Bacteriocins	Antimicrobial peptides	Oilseed cakes, dairy by-products
Exopolysaccharides (EPS)	Polysaccharides secreted by microorganisms	Cereal brans, fruit pomace
Bioactive Peptides	Short protein fragments with health benefits	Cereal brans, oilseed meals
Vitamins	Essential micronutrients	Dairy by-products, brewery residues
Organic Acids	Carboxylic acids with health-promoting properties	Fruit pomace, vegetable trimmings
Cell Wall Fragments	Fragments from microbial cell walls	Dairy by-products, cereal brans
Antioxidant Compounds	Molecules that prevent oxidative stress	Fruit pomace, vegetable trimmings

3. Production Processes and Downstream Processing

Postbiotics are produced out of agro-industrial waste starting with the selection and preparation of the substrate (Behzadnia et al., 2022). The waste stream selected is also dependent on the microbial strain to be employed and the required type of postbiotic (Moradi et al., 2020). Typical raw material is fruit pomace, cereal brans, oilseed cakes and dairy by-products (Quiles et al., 2018). These wastes are also cleaned and then their size is reduced by increasing the surface area and then physical or enzymatic pretreatments are done (Ravindran and Jaiswal, 2016). Bound carbohydrates, proteins, and bioactive compounds are set free by such pretreatments and become more readily accessible to microbial metabolism (Krakowska-Sieprawska et al., 2022). Improving bioavailability of nutrients in these substrates is commonly done using steam explosion, hydrothermal processing and enzymatic hydrolysis (Yadav, 2017).
The most important step in the process of postbiotic production is fermentation in which two are used, submerged fermentation (SmF) and solid-state fermentation (SSF) (Tong et al., 2023). SmF which is commonly applied to liquid or slurry substrates like whey are controlled in terms of temperature, pH and aeration (Tripathi et al., 2015). SSF, which is applicable in fibrous substrates, such as cereal bran or oil seed meals is a natural microbial habitat and tends to lead to higher concentrations of products with reduced use of water (Šelo et al., 2021). In the fermentation process, lactic acid bacteria, bifidobacteria, or other useful microbes decompose the nutrients present in waste to create bioactive metabolites including short-chain fatty acids, bacteriocins, exopolysaccharides, peptides and vitamins (Lim and Abd Rahim, 2025).
After fermentation, the biomass is then inactivated in order to achieve the definition of postbiotics, non-viable microbial preparations (Vinderola et al., 2022). The cells can be killed by heat treatment, high-pressure processing, or by irradiation without greatly degrading the bioactive compounds (Van Impe et al., 2018). The deactivation method to use is dependent on the thermal stability of the metabolites of interest (Ahnoff et al., 2015).
After inactivation, the downstream processing is aimed at isolating the bio actives of the bulk fermentation medium (Agarwal et al., 2020). This could be centrifugation, filtration, membrane separation or precipitation. The final postbiotic may be in the form of crude cell-free supernatant, partially purified extract or highly concentrated and dried powder depending on the application (Rocchetti et al., 2024). Spray drying or freeze-drying is used to increase the shelf life and stability (Lovalenti et al., 2016). The production process is not just aimed at maximizing production but also at producing safe products, reproducible, and meeting regulatory aspect of food or feed utilization (Mattarozzi et al., 2023). Postbiotics production requires a number of important steps, as depicted in Table 2, which comprise preparing a substrate, fermentation, inactivation, and downstream processing.

Table 2: Production and Downstream Processing Steps for Postbiotics

Step	Description	Techniques Used
Substrate Selection	Choosing agro-industrial waste as a fermentation medium	Fruit pomace, cereal bran, dairy whey
Substrate Preparation	Cleaning, size reduction, and pretreatment of waste streams	Steam explosion, enzymatic hydrolysis
Microbial Fermentation	Conversion of waste by beneficial microbes into postbiotics	Submerged fermentation (SmF), SSF
Fermentation Monitoring	Controlling environmental factors during fermentation	pH, temperature, aeration control
Inactivation	Rendering microorganisms non-viable while preserving bioactivity	Heat treatment, high-pressure processing
Downstream Processing	Separation of bioactive compounds from the fermentation medium	Centrifugation, filtration, membrane separation
Purification	Concentration and purification of bioactive metabolites	Precipitation, chromatography
Stabilization	Enhancing the shelf life of postbiotics for final applications	Freeze-drying, spray drying

4. Functional Mechanisms of Postbiotics

The positive actions of postbiotics have various physiological and biochemical mechanisms of effect (Teame et al., 2020). Gut barrier enhancement is one of the primary pathways. The short-chain fatty acids, especially butyrate, induce the secretion of the mucus, enhance the tight junction proteins and promote the renewal of epithelial cells (Parada Venegas et al., 2019). This enhances the intestinal barrier and limits translocation of pathogens and toxins into the blood stream (Awad et al., 2017).

Immune modulation is another mechanism that is also critical (Faist et al., 1996). Pattern recognition receptors of immune cells, including Toll-like receptors, can interact with structural components in the cell wall, including peptidoglycans, lipoteichoic acids and cell wall polysaccharides (Sukhithasri et al., 2013). These connections assist in balancing of pro-inflammatory and anti-inflammatory cytokines reactions, leading to immune tolerance and decrease in chronic inflammation (Cicchese et al., 2018). Postbiotics too are antimicrobial (Rad et al., 2022). Organic acids also reduce the pH of the gut, preventing the growth of harmful bacteria, and bacteriocins are small antimicrobial peptides that have a specific effect on harmful microbes and do not disrupt the beneficial commensals (Dittoe et al., 2018). Reactive oxygen species (ROS)-scavenging metabolites are present in some postbiotics and lower oxidative stress and protect host tissues against damage (Singh et al., 2022). Also, a new field of postbiotic research is metabolic regulation (Zhong et al., 2024). Some of the exopolysaccharides are known to affect lipid metabolism by improving cholesterol profiles, whilst other metabolites increase insulin sensitivity and satiety hormone control (Korcz et al., 2018). Postbiotics indirectly impact nutrient absorption and energy balance by modulating the composition and activity of microbiota of the gut, with overall metabolic health being supported (Deokar et al., 2025). As illustrated in Fig. 1, postbiotics exert their effects through gut barrier enhancement, immune modulation, antimicrobial activity, and metabolic regulation.

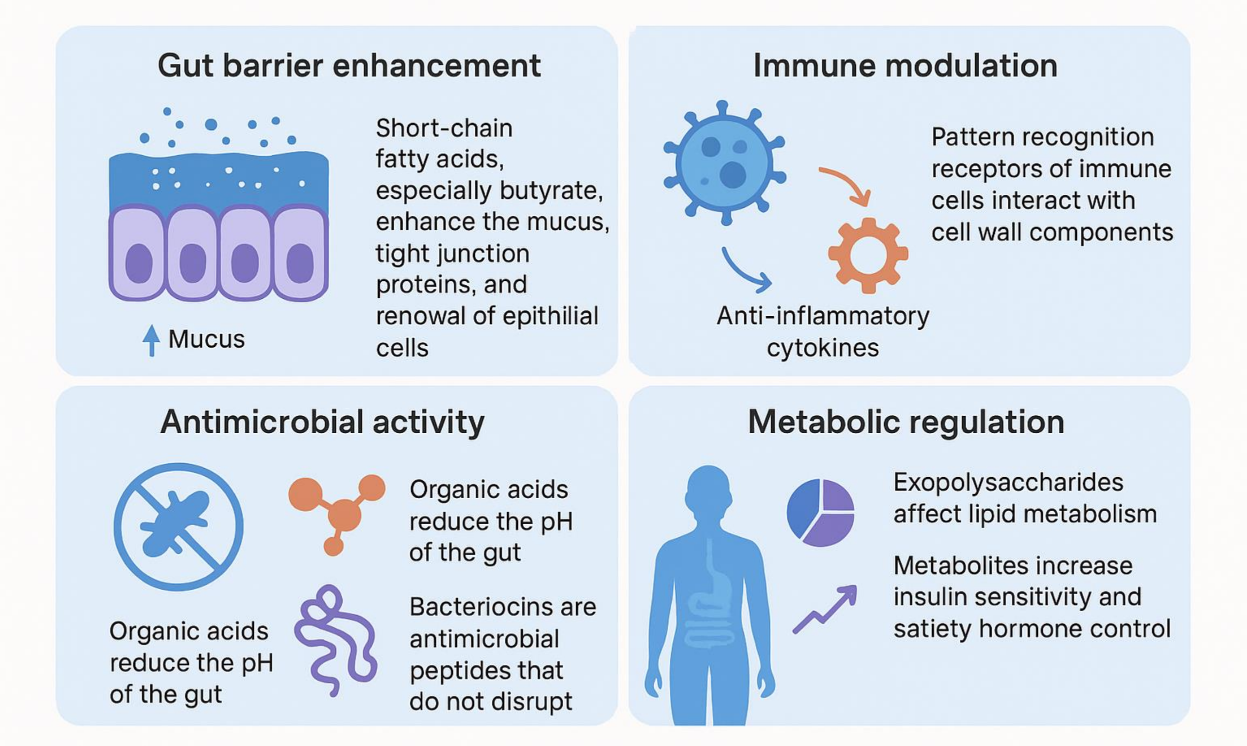

Fig 1: Functional mechanisms of postbiotics

5. Applications in Food, Feed, and Therapeutics

Postbiotics have been found to be useful in the food industry both in terms of functionality and technology (Balthazar et al., 2022). They are stable at extreme temperatures and pHs and can therefore be incorporated into baked products, dairy products, beverages, and snacks (Chuck-Hernandez et al., 2022). Bioactive flavor compounds can be used to extend the shelf life of foods that are spoilable and improve the sensory properties of postbiotic-enriched foods by inhibiting the growth of the spoilage organisms (Kaynakci, 2025). They also provide functional benefits such as providing immune-boosting and antioxidant effects without the need to use live microorganisms (Stephen et al., 2023).

Postbiotics are now the focus in animal feed and they are replacing antibiotic growth promoters (Saeed et al., 2023). It has been incorporated into the diets of poultry, and aquaculture and shown to increase feed efficiency, improve gut morphology, and decrease disease incidence (Van der Aar et al., 2017). They assist in the maintenance of microbial balance in the gut, stimulation of the immune system and increase nutrient digestibility (Adedokun and Olojede, 2019). This is especially useful in intensive agro-ecosystems where the disease pressure is quite severe and the regulatory measures on the use of antibiotics are escalating (Pradhan et al., 2025). Postbiotics are also being investigated in therapeutic usage in the prevention and treatment of gastrointestinal diseases, metabolic syndrome, allergies, skin diseases (Abbasi et al., 2022). Their non-viability nature lowers the risks of using live probiotics like infecting people with weak immunity (Bernardeau and Cretenet, 2019). Moreover, particular postbiotic metabolites are being explored as complementary treatments of inflammatory bowel disease, obesity, type 2 diabetes, and heart diseases (Mishra et al., 2024). Postbiotics may be useful in dermal applications to enhance skin barrier maintenance and local immune responses, and this represents a potential in skin and cosmetic previous formulations (da Silva Vale et al., 2023).

6. Challenges and Future Perspectives

Although promising, the high-scale use of postbiotics as a byproduct of agro-industrial waste is limited by a number of challenges in which one of them is the matter of standardization (Timmermans and Epstein, 2010). Agro-wastes and their composition vary on a batch-to-batch basis due to the nature of crops cultivated, seasonal, and processing, leading to differences in yield and bioactivity of the postbiotic (Coscueta et al., 2025). In order to be passed by the regulator and ensure consumer confidence, there is the need to establish standard production guidelines and analytical procedures of characterization (Prylipko et al., 2021). The other difficulty is to scale up production. Whereas fermentation at laboratory scale is highly controlled, industrial-scale processes must handle raw materials that are not controlled, the risk of contamination, and optimizing the process economically (Meyer et al., 2017). Further, the inactivation and drying methods employed must be chosen in such a way that they find a balance between microbial and bioactive compound preservation (Morgan et al., 2006).

Another area that should be covered is mechanistic understanding (Shiroda et al., 2024). The bioactive molecules and the mechanism of action of most of the positive impacts of postbiotics are not known to date (Jastrząb et al., 2021). Pragmatic solutions to the identification of important compounds, their biosynthetic route, and targets in hosts can be found in genomics, metabolomics and proteomics in order to use more specific production strategies (Wolfender et al., 2019).

Regulatory systems of postbiotics in most regions are underdeveloped (Yunes et al., 2022). They should be given a set of standards on how to define, do safety tests, substantiate health claims, labeling and make it easy to enter the market. Academia, industry, and policymakers will have to collaborate with the goal of reaching the global consensus (Pattyn et al., 2022).

Agro-waste in the future needs to be regarded as a source of biomass, as well as co-fermentation solutions, which implies the use of multiple different species of microorganisms is capable of synthesizing postbiotic blends with a synergistic set of bioactivities (Montefrio et al., 2025). The production would be made more efficient with new bioprocess engineering systems like continuous fermentation and membrane bioreactors (Hemmerich et al., 2018). A combination of these technologies and measurements of sustainability is sure to ensure that the production of postbiotics not only contribute to the promotion of health but also operates in accordance with the goals and objectives of the circular economy (Moradi et al., 2020).

7. Conclusion

The application of agro industrial waste in the manufacture of postbiotics is a strong and progressive method of solving environmental and health concerns. The concept can be used to pursue the ideas of the circular bioeconomy that will convert the nutrient-enriching by-products to stable bioactive compounds to become food and feed products and therapeutic products. Postbiotics possess certain advantages to probiotics including increased safety, stability and capability to be added to an extensive selection of items, which makes them highly attractive to industry stakeholders. Their production is being advanced by the improvement in fermentation technology, downstream processing, functional characterization and yet there are issues of standardization, regulatory certainty and optimization of the processes on large scale. Further studies and intersectoral cooperation will see agro-waste-derived postbiotics becoming one of the backbones of sustainable health solutions, as they achieve waste reduction, efficiency, and a healthier world at the same time.

References

1. Abbasi, A., Rad, A. H., Ghasempour, Z., Sabahi, S., Kafil, H. S., Hasannezhad, P., ... & Shahbazi, N. (2022). The biological activities of postbiotics in gastrointestinal disorders. Critical Reviews in Food Science and Nutrition, 62(22), 5983-6004.
2. Adedokun, S. A., & Olojede, O. C. (2019). Optimizing gastrointestinal integrity in poultry: the role of nutrients and feed additives. Frontiers in Veterinary Science, 5, 348.
3. Agarwal, A., Jaiswal, N., Tripathi, A. D., & Paul, V. (2020). Downstream processing; applications and recent updates. In Bioprocessing for Biofuel Production: Strategies to Improve Process Parameters (pp. 29-55). Singapore: Springer Singapore.
4. Ahnoff, M., Cazares, L. H., & Sköld, K. (2015). Thermal inactivation of enzymes and pathogens in biosamples for MS analysis. Bioanalysis, 7(15), 1885-1899.
5. Awad, W. A., Hess, C., & Hess, M. (2017). Enteric pathogens and their toxin-induced disruption of the intestinal barrier through alteration of tight junctions in chickens. Toxins, 9(2), 60.
6. Balthazar, C. F., Guimarães, J. F., Coutinho, N. M., Pimentel, T. C., Ranadheera, C. S., Santillo, A., ... & Sant'Ana, A. S. (2022). The future of functional food: Emerging technologies application on prebiotics, probiotics and postbiotics. Comprehensive Reviews in Food Science and Food Safety, 21(3), 2560-2586.
7. Behzadnia, A., Moosavi-Nasab, M., Mohammadi, A., Babajafari, S., & Tiwari, B. K. (2022). Production of an ultrasound-assisted biosurfactant postbiotic from agro-industrial wastes and its activity against Newcastle virus. Frontiers in nutrition, 9, 966338.
8. Bernardeau, M., & Cretenet, M. (2019). Probiotic Effects of non-viable lactic acid bacteria. In Lactic Acid Bacteria (pp. 609-629). CRC Press.
9. Chuck-Hernandez, C., García-Cayuela, T., & Méndez-Merino, E. (2022). Dairy-based snacks. In Snack Foods (pp. 417-448). CRC Press.
10. Cicchese, J. M., Evans, S., Hult, C., Joslyn, L. R., Wessler, T., Millar, J. A., ... & Kirschner, D. E. (2018). Dynamic balance of pro-and anti-inflammatory signals controls disease and limits pathology. Immunological reviews, 285(1), 147-167.

11. Coscueta, E., Brassesco, M. E., Machado, M., Borges, S., Coelho, M., Gómez-García, R., & Campos, D. (2025, September). CIPCA2025: X international Conference on food proteins and colloids. In X International Conference on Food Proteins and Colloids. Universidade Católica Portuguesa.
12. Cuevas-González, P. F., Liceaga, A. M., & Aguilar-Toalá, J. E. (2020). Postbiotics and paraprobiotics: From concepts to applications. Food Research International, 136, 109502. https://doi.org/10.1016/j.foodres.2020.109502
13. da Silva Vale, A., de Melo Pereira, G. V., de Oliveira, A. C., de Carvalho Neto, D. P., Herrmann, L. W., Karp, S. G., ... & Soccol, C. R. (2023). Production, formulation, and application of postbiotics in the treatment of skin conditions. Fermentation, 9(3), 264.
14. Deokar, G. S., Kshirsagar, S. J., Shinde, Y. A., Pathak, V. A., & Nirmal, N. P. (2025). Postbiotics-promising role as energetic biomolecules, safety regulations, and nutritional aspects. In Postbiotics (pp. 709-736). Academic Press.
15. Dittoe, D. K., Ricke, S. C., & Kiess, A. S. (2018). Organic acids and potential for modifying the avian gastrointestinal tract and reducing pathogens and disease. Frontiers in veterinary science, 5, 216.
16. Faist, E., Schinkel, C., & Zimmer, S. (1996). Update on the mechanisms of immune suppression of injury and immune modulation. World journal of surgery, 20(4), 454-459.
17. Hemmerich, J., Noack, S., Wiechert, W., & Oldiges, M. (2018). Microbioreactor systems for accelerated bioprocess development. Biotechnology journal, 13(4), 1700141.
18. Jastrząb, R., Graczyk, D., & Siedlecki, P. (2021). Molecular and cellular mechanisms influenced by postbiotics. International journal of molecular sciences, 22(24), 13475.
19. Kaynakci, E. C. (2025). Evaluation of alginate-based coatings enriched with postbiotics from Bifidobacterium spp. on the quality and safety of Turkey meat. Scientific Reports, 15(1), 23634.
20. Korcz, E., Kerényi, Z., & Varga, L. (2018). Dietary fibers, prebiotics, and exopolysaccharides produced by lactic acid bacteria: potential health benefits with special regard to cholesterol-lowering effects. Food & function, 9(6), 3057-3068.
21. Krakowska-Sieprawska, A., Kiełbasa, A., Rafińska, K., Ligor, M., & Buszewski, B. (2022). Modern methods of pre-treatment of plant material for the extraction of bioactive compounds. Molecules, 27(3), 730.
22. Lau, K. Q., Sabran, M. R., & Shafie, S. R. (2021). Utilization of vegetable and fruit by-products as functional ingredient and food. Frontiers in nutrition, 8, 661693.
23. Lim, E. J., & Abd Rahim, M. H. (2025). Fermentation for Enhanced Biosynthesis and Bioavailability of Micronutrients, Prebiotics, Bioactive Peptides and Functional Fatty Acids in Food Products. International Journal of Advanced Research in Food Science and Agriculture Technology, 4(1), 9-27.
24. Lovalenti, P., Anderl, J., Yee, L., Nguyen, V., Ghavami, B., Ohtake, S., ... & Truong-Le, V. (2016). Stabilization of Live Attenuated Influenza Vaccines by Freeze Drying, Spray Drying, and Foam Drying. Pharmaceutical research, 33(5).
25. Markowiak, P., & Śliżewska, K. (2018). The role of probiotics, prebiotics and synbiotics in animal nutrition. Gut Pathogens, 10, 21. https://doi.org/10.1186/s13099-018-0250-0
26. Mattarozzi, M., Laski, E., Bertucci, A., Giannetto, M., Bianchi, F., Zoani, C., & Careri, M. (2023). Metrological traceability in process analytical technologies and point-of-need technologies for food safety and quality control: Not a straightforward issue. Analytical and Bioanalytical Chemistry, 415(1), 119-135.
27. Meyer, H. P., Minas, W., & Schmidhalter, D. (2017). Industrial-scale fermentation. Industrial biotechnology: products and processes, 1-53.
28. Mirabella, N., Castellani, V., & Sala, S. (2014). Current options for the valorization of food manufacturing waste: A review. Journal of Cleaner Production, 65, 28–41.
29. Mishra, N., Garg, A., Ashique, S., & Bhatt, S. (2024). Potential of postbiotics for the treatment of metabolic disorders. Drug Discovery Today, 29(4), 103921.
30. Montefrio, J., Galvan, C., Dionela, S., Guillermo, I., & Caipang, C. (2025). Turning losses into opportunities: waste valorization and its potential application in the production of Philippine commodities. Journal of Biological Studies, 8(1), 1-33.
31. Moradi, M., Guimarães, J. T., & Balthazar, C. F. (2020). Postbiotics: Definition, characteristics and potential applications. Trends in Food Science & Technology, 100, 1–15.
32. Moradi, M., Kousheh, S. A., Almasi, H., Alizadeh, A., Guimarães, J. T., Yılmaz, N., & Lotfi, A. (2020). Postbiotics produced by lactic acid bacteria: The next frontier in food safety. Comprehensive reviews in food science and food safety, 19(6), 3390-3415.
33. Morgan, C. A., Herman, N., White, P. A., & Vesey, G. (2006). Preservation of micro-organisms by drying; a review. Journal of microbiological methods, 66(2), 183-193.
34. Mussatto, S. I., & Dragone, G. (2016). Biomass pretreatment, biorefineries, and value-added products from agro-industrial wastes. Bioresource Technology, 215, 3–8.

35. Nayak, A., & Bhushan, B. (2019). An overview of the recent trends on the waste valorization techniques for food wastes. Journal of Environmental Management, 233, 352–370.
36. Parada Venegas, D., De la Fuente, M. K., Landskron, G., González, M. J., Quera, R., Dijkstra, G., ... & Hermoso, M. A. (2019). Short chain fatty acids (SCFAs)-mediated gut epithelial and immune regulation and its relevance for inflammatory bowel diseases. Frontiers in immunology, 10, 277.
37. Patel, S., Shukla, R., & Goyal, A. (2021). Probiotics, prebiotics and postbiotics: A review on functional food and nutraceuticals. Journal of Food Science and Technology, 58, 4399–4412.
38. Pattyn, V., Blum, S., Fobé, E., Pekar-Milicevic, M., & Brans, M. (2022). Academic policy advice in consensus-seeking countries: The cases of Belgium and Germany. International Review of Administrative Sciences, 88(1), 26-42.
39. Pereira, M. A., & Vicente, A. A. (2010). Waste to wealth: Valorisation of agro-food by-products. Biotechnology Advances, 28(6), 856–868.
40. Pradhan, S. S., Mahanty, A., Pattanaik, K. P., Adak, T., & Mohapatra, P. K. (2025). Entry, fate and impact of antibiotics in rice agroecosystem: a comprehensive review. Environmental Science and Pollution Research, 32(3), 1120-1138.
41. Prylipko, T. M., Kostash, V. B., Fedoriv, V. M., Lishchuk, S. H., & Tkachuk, V. P. (2021). Control and identification of food products under EC regulations and standards. International Journal of Agricultural Extension.
42. Quiles, A., Campbell, G. M., Struck, S., Rohm, H., & Hernando, I. (2018). Fiber from fruit pomace: A review of applications in cereal-based products. Food Reviews International, 34(2), 162-181.
43. Rad, A. H., Hosseini, S., & Pourjafar, H. (2022). Postbiotics as dynamic biological molecules for antimicrobial activity: A mini-review. Biointerface Res. Appl. Chem, 12(5), 6543-6556.
44. Ravindran, R., & Jaiswal, A. K. (2016). A comprehensive review on pre-treatment strategy for lignocellulosic food industry waste: challenges and opportunities. Bioresource technology, 199, 92-102.
45. Rocchetti, M. T., Russo, P., De Simone, N., Capozzi, V., Spano, G., & Fiocco, D. (2024). Immunomodulatory activity on human macrophages by cell-free supernatants to explore the probiotic and postbiotic potential of Lactiplantibacillus plantarum strains of plant origin. Probiotics and Antimicrobial Proteins, 16(3), 911-926.
46. Sadh, P. K., Duhan, S., & Duhan, J. S. (2018). Agro-industrial wastes and their utilization using solid state fermentation: a review. Bioresources and bioprocessing, 5(1), 1-15.
47. Saeed, M., Afzal, Z., Afzal, F., Khan, R. U., Elnesr, S. S., Alagawany, M., & Chen, H. (2023). Use of postbiotic as growth promoter in poultry industry: A review of current knowledge and future prospects. Food science of animal resources, 43(6), 1111.
48. Salminen, S., Collado, M. C., Endo, A., Hill, C., Lebeer, S., Quigley, E. M., … Vinderola, G. (2021). The ISAPP consensus statement on the definition and scope of postbiotics. Nature Reviews Gastroenterology & Hepatology, 18(9), 649–667.
49. Šelo, G., Planinić, M., Tišma, M., Tomas, S., Koceva Komlenić, D., & Bucić-Kojić, A. (2021). A comprehensive review on valorization of agro-food industrial residues by solid-state fermentation. Foods, 10(5), 927.
50. Shiroda, M., Franovic, C. G. C., de Lima, J., Noyes, K., Babi, D., Beltran-Flores, E., ... & Stoltzfus, J. R. (2024). Examining and supporting mechanistic explanations across chemistry and biology courses. CBE—Life Sciences Education, 23(3), ar38.
51. Singh, V., Ahlawat, S., Mohan, H., Gill, S. S., & Sharma, K. K. (2022). Balancing reactive oxygen species generation by rebooting gut microbiota. Journal of Applied Microbiology, 132(6), 4112-4129.
52. Stephen, J., Manoharan, D., & Radhakrishnan, M. (2023). Immune boosting functional components of natural foods and its health benefits. Food production, processing and nutrition, 5(1), 61.
53. Sukhithasri, V., Nisha, N., Biswas, L., Kumar, V. A., & Biswas, R. (2013). Innate immune recognition of microbial cell wall components and microbial strategies to evade such recognitions. Microbiological research, 168(7), 396-406.
54. Teame, T., Wang, A., Xie, M., Zhang, Z., Yang, Y., Ding, Q., ... & Zhou, Z. (2020). Paraprobiotics and postbiotics of probiotic Lactobacilli, their positive effects on the host and action mechanisms: A review. Frontiers in nutrition, 7, 570344.
55. Timmermans, S., & Epstein, S. (2010). A world of standards but not a standard world: Toward a sociology of standards and standardization. Annual review of Sociology, 36(1), 69-89.
56. Tong, Y., Guo, H. N., Abbas, Z., Zhang, J., Wang, J., Cheng, Q., ... & Zhang, R. (2023). Optimizing postbiotic production through solid-state fermentation with Bacillus amyloliquefaciens J and Lactiplantibacillus plantarum SN4 enhances antibacterial, antioxidant, and anti-inflammatory activities. Frontiers in Microbiology, 14, 1229952.
57. Tripathi, A. D., Srivastava, S. K., Singh, P., Singh, R. P., Singh, S. P., Jha, A., & Yadav, P. (2015). Optimization of process variables for enhanced lactic acid production utilizing paneer whey as substrate in SMF. Applied Food Biotechnology, 2(2), 46-55.

58. Van der Aar, P. J., Molist, F. V., & Van Der Klis, J. D. (2017). The central role of intestinal health on the effect of feed additives on feed intake in swine and poultry. Animal feed science and technology, 233, 64-75.
59. Van Impe, J., Smet, C., Tiwari, B., Greiner, R., Ojha, S., Stulić, V., ... & Režek Jambrak, A. (2018). State of the art of nonthermal and thermal processing for inactivation of micro-organisms. Journal of applied microbiology, 125(1), 16-35.
60. Vinderola, G., Sanders, M. E., & Salminen, S. (2022). The concept of postbiotics. Foods, 11(8), 1077.
61. Wang, C., Liu, Z., Zhou, T., Wu, J., Feng, F., Wang, S., … Xu, K. (2025). Gut microbiota-derived butyric acid regulates calcific aortic valve disease pathogenesis by modulating GAPDH lactylation and butyrylation. iMeta, e70048.
62. Wegh, C. A., Geerlings, S. Y., Knol, J., Roeselers, G., & Belzer, C. (2019). Postbiotics and their potential applications in early life nutrition and beyond. International Journal of Molecular Sciences, 20(19), 4673.
63. Wolfender, J. L., Litaudon, M., Touboul, D., & Queiroz, E. F. (2019). Innovative omics-based approaches for prioritisation and targeted isolation of natural products–new strategies for drug discovery. Natural product reports, 36(6), 855-868.
64. Yadav, S. K. (2017). Technological advances and applications of hydrolytic enzymes for valorization of lignocellulosic biomass. Bioresource technology, 245, 1727-1739.
65. Yunes, R. A., Poluektova, E. U., Belkina, T. V., & Danilenko, V. N. (2022). Lactobacilli: Legal regulation and prospects for new generation drugs. Applied Biochemistry and Microbiology, 58(5), 652-664.
66. Zeng, M., Zou, Y., Shi, Z., Wang, J., Yang, Y., Bai, Y., … Zhou, Y. (2020). Advances in lactic acid bacteria fermentation and functional metabolite production. LWT, 201, 116219.
67. Zhong, Y., Wang, T., Luo, R., Liu, J., Jin, R., & Peng, X. (2024). Recent advances and potentiality of postbiotics in the food industry: Composition, inactivation methods, current applications in metabolic syndrome, and future trends. Critical Reviews in Food Science and Nutrition, 64(17), 5768-5792.
68. Żółkiewicz, J., Marzec, A., Ruszczyński, M., & Feleszko, W. (2020). Postbiotics—A step beyond pre- and probiotics. Nutrients, 12(8), 2189.