Psycbiotic Agents:The Neuroactive Metabolites of Probiotics

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Abstract. The gut–brain axis has attracted growing attention, given that microbial activity can significantly influence host neurophysiology. Central to this interaction are biogenic amines, including serotonin, dopamine, gamma-aminobutyric acid (GABA), tryptamine and phenylethylamine, which are synthesised by selected probiotic strains as microbial metabolites. These metabolites act as postbiotic agents, maintaining biological activity independently of bacterial viability and representing a mechanistic link between gut bacteria and mental health. Both gut-resident probiotics and fermented products are sources of these compounds, as microbial communities transform dietary substrates into various neuroactive molecules. This metabolic capacity underscores the role of gut bacteria as functional hubs that produce psychobiotic agents. By modulating neurotransmission, immune responses and stress-related pathways, postbiotic biogenic amines provide the basis for innovative nutritional and therapeutic approaches. The interplay between probiotics, their metabolites, and fermentation-derived postbiotics emphasises their potential for supporting mental well-being.

Keywords: Biogenic amines, microbial metabolites, probiotics, postbiotics, fermented products, gut bacteria, psychobiotics.

1 Introduction

The human gut microbiota has emerged as a critical regulator of overall health and well-being. The bidirectional communication network connecting intestinal microorganisms with the central nervous system, known as the microbiota–gut–brain axis (MGBA), plays a pivotal role in regulating stress, cognition, and emotional balance (Marano et al., 2023). This has accelerated the development of next-generation functional biotics,

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including probiotics, postbiotics, prebiotics and synbiotics, which act as neuroactive modulators with significant implications for mental health (Schneider et al., 2024).
Probiotics are basically living microorganisms that can do you good if you've got enough of them (Ranjha et al., 2021; Karukuvelraja & Saranya, 2025). As well as maintaining intestinal homeostasis, they exert systemic and neural effects through immune and endocrine pathways (Park et al., 2025). Certain Lactobacillus and Bifidobacterium strains synthesise bioactive biogenic amines, such as serotonin, dopamine, gamma-aminobutyric acid (GABA) and tryptamine, that act as microbial neurotransmitters, influencing neuronal signalling and behaviour (Ramesh et al., 2024; Bleibel et al., 2023; Du et al., 2024). These metabolites are considered key psychobiotic molecules that facilitate communication between gut microorganisms and the host's central nervous system (Cryan et al., 2021).

Notwithstanding their well-documented benefits, probiotic applications are confronted with challenges related to strain viability, safety concerns, and variability in host colonization (Merenstein et al., 2023; Vinderola et al., 2022). These limitations have shifted scientific attention towards postbiotics — non-viable microbial cells, cell fragments and their metabolic products that exert biological activity regardless of cell viability (Prajapati et al., 2023). Postbiotics include peptides, organic acids, and short-chain fatty acids.

1.1 Functional Biotics and Their Neuroactive Mechanisms

The concept of functional biotics has evolved substantially over the past decade. Initially, the term referred exclusively to probiotics—live microorganisms that, when administered in adequate amounts, confer measurable health benefits to the host. Today, it encompasses a broader spectrum of bioactive agents, including inactivated microbial cells and their metabolites, which exert distinct physiological and neurological effects (Schneider et al., 2024). Functional biotics now unite several categories—probiotics, prebiotics, synbiotics, paraprobiotics, and postbiotics—all defined by their capacity to modulate host health through microbiota-mediated mechanisms (Salminen et al., 2021). According to the International Scientific Association for Probiotics and Prebiotics (ISAPP), postbiotics are "preparations of inanimate microorganisms and/or their components that confer a health benefit on the host" (Salminen et al., 2021). This definition represents the latest stage in the conceptual evolution of functional biotics. Postbiotics include non-viable microbial cells and cell-free supernatants enriched with peptides, short-chain fatty acids (SCFAs), exopolysaccharides, and other soluble molecules (fig.. 1) with biological activity ((Yeşilyurt, et al., 2021;
Xin et al., 2024).

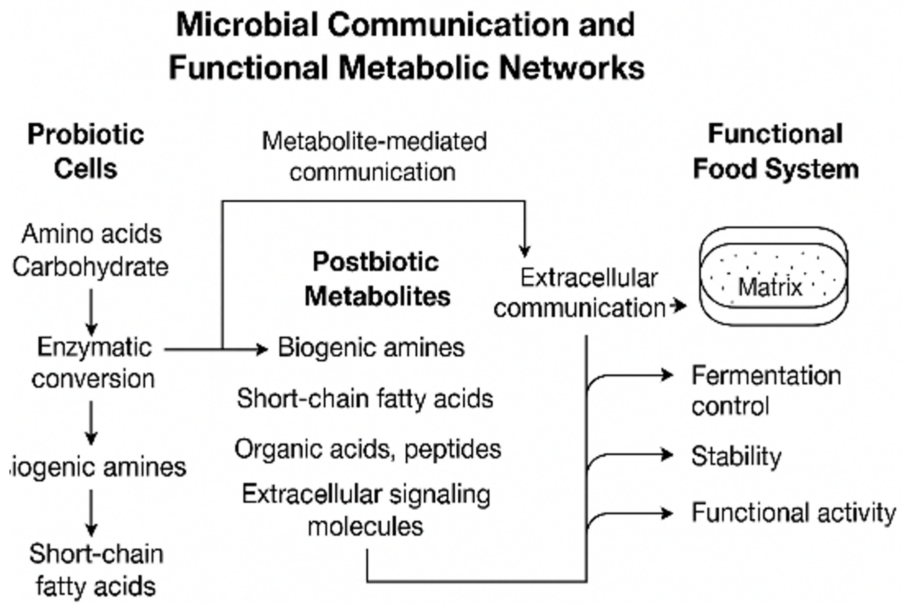

Fig. 1. Microbial Communication and Functional Metabolic Networks

Compared with live probiotics, postbiotics provide greater stability, safety, and formulation flexibility, as they are not subject to challenges such as antibiotic resistance or colonization variability (El Far et al., 2023). Moreover, postbiotic metabolites—particularly SCFAs and bioactive peptides—are increasingly recognized for their antioxidant, immunomodulatory, and neuroactive properties, bridging microbiome research with functional food and biotechnology (Moradi et al., 2020). This paradigm shift—from microbial viability to functional efficacy—marks a turning point in microbial therapeutics, paving the way for precision fermentation and the development of biofunctional ingredients with defined psychobiotic potential.

1.2 Mechanisms of Action of Functional and Psychobiotic Systems

Functional and psychobiotic systems influence the host through interconnected metabolic, immune, endocrine, and barrier-regulating pathways that collectively sustain gut–brain communication (Lei et al., 2023).

A primary mechanism is metabolic modulation via short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate. These metabolites regulate host energy metabolism, enhance mitochondrial efficiency, and exhibit neuroprotective properties Mohammad &Thiemermann, 2021). In addition, SCFAs and microbial-derived peptides balance cytokine production and suppress inflammatory cascades, contributing to systemic homeostasis (Mansuy-Aubert & Ravussin, 2023).

At the neuroendocrine level, microbial metabolites modulate the hypothalamic–pituitary–adrenal (HPA) axis, influencing stress response and cortisol regulation (Bertollo et al., 2025). SCFAs and amino acid derivatives such as tryptophan metabolites affect corticotropin-releasing hormone (CRH) and adrenocorticotropic hormone (ACTH) release, linking microbial activity to endocrine balance (Rusch et al., 2023).

Immune modulation forms another core mechanism. Functional microbial products increase anti-inflammatory cytokines such as IL-10 while reducing TNF-α and IL-6, thereby promoting macrophage polarization and T-regulatory (Treg) responses (Zhang et al., 2023; Duan et al., 2023).

In parallel, functional metabolites enhance intestinal barrier integrity by upregulating tight junction proteins (occludin, claudin) and stimulating mucin production (Lan et al., 2024; (Yeşilyurt, et al., 2021). This reinforcement reduces translocation of endotoxins such as lipopolysaccharides (LPS), preventing systemic inflammation and maintaining microbial equilibrium ((Wallace,& Milev,2017; Mansuy-Aubert & Ravussin, 2023).

Within this framework, serotonin, dopamine, γ-aminobutyric acid (GABA), tryptamine, and phenylethylamine—represent central psychobiotic mediators. Produced mainly by *Lactobacillus* and *Bifidobacterium* species, these metabolites influence mood, cognition, and stress adaptation through vagal and humoral signaling routes (Jang et al., 2024; Asokan & Kumar, 2025; Alagiakrishnan et al., 2024). Their synthesis pathways, particularly decarboxylation of amino acid precursors, form the biochemical foundation of psychobiotic activity (Kyei-Baffour et al., 2025).

Collectively, these findings illustrate (Fig. 2) that functional and psychobiotic systems operate as biochemical bridges between the gut microbiota and the brain, integrating metabolic, immune, and neurochemical networks to sustain host physiological and psychological balance (Zandifar et al., 2025).

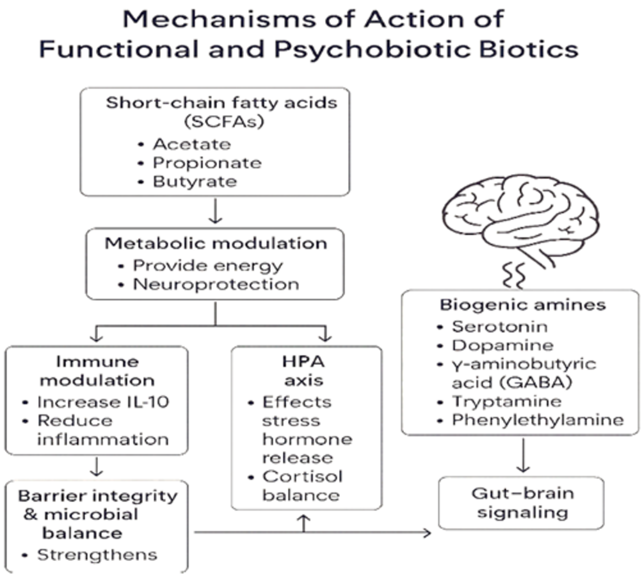

Fig. 2. Mechanisms of Action of Functional and Psychobiotic Biotics

2 Biogenic Amines and Neuroactive Metabolites: The Chemical Core of Psychobiotic Action

Some lactic acid bacteria have specialised enzymatic systems that allow them to synthesise neuroactive biogenic amines, which are key mediators of microbiota–gut–brain communication. For instance, *Lactobacillus brevis* and *L. plantarum* convert glutamate to GABA (γ-aminobutyric acid) via glutamate decarboxylase (GAD), a process that is commonly used as an indicator of psychobiotic potential (Śliwka et al., 2025a). In a similar way, the metabolism of tryptophan is influenced by *Bifidobacterium* infantis and L. helveticus, with these bacteria generating indole derivatives and serotonin precursors (Chen et al., 2025).

GABA is one of the psychobiotic metabolites that has been most thoroughly characterised. Basically, it's made by certain types of bacteria like L. plantarum, L. rhamnosus, and Bifidobacterium breve, and it's like the main thing that stops you getting anxious and stressed. It does this by messing with the hypothalamic–pituitary–adrenal (HPA) axis, which is like your stress response (Gomes, 2023; Bleibel et al., 2025).

Serotonin (5-HT), which is largely produced from tryptophan by Enterococcus faecium and Streptococcus thermophilus, accounts for almost 90% of peripheral serotonin. The gut-derived hormone serotonin affects mood, thinking, and bowel movements by activating special cells in the gut and using nerves (Margoob et al., 2024; Hwang, 2025) Dopamine biosynthesis from tyrosine occurs in Bacillus subtilis and L. brevis, with the resulting catecholamines contributing to emotional regulation and balance. The influence of these microbial catecholamines on prefrontal–limbic circuits that mediate motivation and stress resilience has been demonstrated (Asokan & Kumar, 2025; LaGreca et al., 2021).

Table 1. Biosynthetic Pathways of Biogenic Amines

Metabolite / Biogenic Amine	Psychobiotic Role / Neurofunction	Origin Type	Mechanism (Gut–Brain Axis)	Representative Strains	Key References (2020–2025)
γ-Aminobutyric Acid (GABA)	Inhibitory neurotransmitter; reduces anxiety and stress	Probiotic & Postbiotic	Activates vagal pathways; increases BDNF and hippocampal GABA receptors	*Lactobacillus plantarum*, *Bifidobacterium breve*	Gomes, P. (2023); Bleibel et al., 2023
Serotonin (5-HT)	Regulates mood, sleep, gut motility	Probiotic	Stimulates enterochromaffin cells; vagal signaling to CNS	*Enterococcus faecium*, *Streptococcus thermophilus*	Margoob et al., 2024; Hwang, 2025
Dopamine	Reinforcement, motivation, cognition	Probiotic & Postbiotic	Tyrosine metabolism; affects catecholaminergic tone	*Lactobacillus brevis*, *Bacillus subtilis*	Asokan & Kumar, 2025.
Tryptamine / Indoles	Serotonin receptor agonist; neurogenesis, circadian regulation	Postbiotic	Acts on $5\text{-HT}_4/5\text{-HT}_7$; crosses gut–brain barrier via vagus and humoral routes	*Clostridium sporogenes*, *Bacteroides fragilis*	Yilmaz et al., 2022, Głowacka et al., 2024
Phenylethylamine (PEA)	Trace amine neuromodulator; improves alertness and mood	Probiotic & Postbiotic	Enhances dopaminergic transmission and cortical activation	*Lactobacillus plantarum*, *Enterococcus faecalis*	Gomes, 2023

Metabolite / Biogenic Amine	Psychobiotic Role / Neurofunction	Origin Type	Mechanism (Gut–Brain Axis)	Representative Strains	Key References (2020–2025)
Histamine	Dual neuroimmune modulator; mediates arousal and inflammation	Postbiotic	HDC-mediated production; influences microglia and HPA axis	*Lactobacillus hilgardii*, *Oenococcus oeni*	Moradi et al., 2020; Amobonye et al., 2025; Carthy, E., & Ellender, 2021.
Polyamines (Putrescine, Cadaverine, Spermidine)	Neuroprotective and pro-cognitive factors	Postbiotic	Polyamine synthesis; improves synaptic stability, stress resilience	*Lactobacillus curvatus*, *Brevibacterium linens*	Yeşilyurt, et al., 2021; Moradi et al., 2020; Barbosa et al., 2024

Enterococcus faecium and *Streptococcus thermophilus* generate dopamine and phenylethylamine from tyrosine, thereby contributing to the biochemical diversity of fermented products (Bleibel et al., 2023). The functional and sensory qualities of fermented foods are shaped by these metabolites, which influence pH stability, flavour, and antioxidant capacity, while simultaneously participating in host signaling pathways (Mishra et al., 2024). Consequently, biogenic amines serve as both biofunctional molecules and quality markers within fermentation systems.

Psychobiotic metabolites as biotechnological targets

The emerging focus in food biotechnology is on directing microbial metabolism towards specific neuroactive compounds. Target metabolites can be modulated by controlled fermentation parameters. These include pH, substrate type and co-culturing. This enables the development of psychobiotic-enriched food matrices. These have predictable neuroactive profiles (Karukuvelraja & Saranya, 2025). Microorganisms produce a broad spectrum of neuroactive metabolites, including GABA, serotonin, dopamine, tryptamine, phenylethylamine and histamine, mainly through decarboxylation and transformation reactions of amino acids (Barbosa et al., 2024). These metabolites collectively participate in microbiota–gut–brain signalling.

Their incorporation into functional foods guarantees consistent bioactivity, reliable fermentation results, prolonged shelf life, and the maintenance of biochemical functionality in products aimed at enhancing cognitive or metabolic function (Scott, et al., 2022). The biochemical link between microbial metabolism and psychobiotic function is ultimately represented by biogenic amines and related neuroactive metabolites. The next generation of microbial products is defined by their controlled synthesis, accumulation, and stabilization, where food-grade fermentation and postbiotic technology converge to produce reproducible, neuroactive, and functionally robust compounds for advanced nutritional and biotechnological applications (Hua et al., 2022).

3 Postbiotic Metabolites: Technological and Functional Significance

Postbiotic metabolites have emerged as key functional components in food biotechnology, integrating microbial functionality with technological stability. Unlike probiotics, postbiotics remain bioactive after processing and storage, ensuring consistent biochemical effects independent of cell viability (Amobonye et al., 2025). Their stability and predictability make them suitable for industrial applications, particularly in fermentation control, food preservation, and the design of functional products (Yılmaz et al., 2022).

Postbiotic compounds—including organic acids, peptides, bacteriocins, and exopolysaccharides—support both the safety and sensory attributes of food systems. Organic acids such as lactic, acetic, and butyric acids lower pH, inhibit spoilage microorganisms, and contribute to flavour development. Bacteriocins and antimicrobial peptides provide natural preservation, reducing reliance on synthetic additives (Vinderola et al., 2022), while exopolysaccharides enhance texture and water retention in both dairy and plant-based formulations (Karukuvelraja & Saranya, 2025).

Optimising fermentation parameters—such as temperature, pH, carbon sources, and co-culture strategies—enables standardised postbiotic profiles and scalable production, achieving functional reproducibility that surpasses the variability associated with live microbial cultures (Mishra et al., 2024b). Incorporation of postbiotics into food matrices improves shelf life, biochemical uniformity, and potential health-related benefits, including modulation of amino acid–derived neuroactive metabolites and enhancement of digestive functions (Śliwka et al., 2025b; Chen et al., 2025).

3.1 Psychobiotic Agents: Metabolic and Biochemical Perspectives

The concept of psychobiotic agents integrates microbial metabolism with biochemical communication mechanisms between microorganisms and their environment. Modern psychobiotics emphasise metabolic functionality over microbial viability, with psychobiotic activity primarily determined by metabolite profiles rather than cell survival (Slykerman et al., 2025; Kyei-Baffour et al., 2025; Bleibel et al., 2025). Early studies demonstrated that certain lactic acid bacteria synthesise neuroactive molecules such as GABA and serotonin, influencing central nervous system signalling (Alagiakrishnan et al., 2024). Recent work positions these metabolites as functional biomolecules in food biotechnology, with applications in precision fermentation and psychobiotic-enriched products (Rocchetti et al., 2025).

Postbiotic derivatives—consisting of inactivated microbial biomass and secreted metabolites—serve as reproducible metabolic platforms with enhanced safety and stability (Islam et al., 2024; Zhu et al., 2025). Thermal, enzymatic, or mechanical inactivation

preserves key metabolites such as peptides, short-chain fatty acids, and amino acid derivatives, which maintain bioactivity, modulate fermentation kinetics, and influence co-cultured strains (Amobonye et al., 2025).
This shift represents a paradigm change in microbial biotechnology: survival-based probiotic models are increasingly complemented or replaced by metabolite-driven psychobiotic systems. Microbial metabolites now form the fundamental building blocks for functional innovation, bridging food science, metabolic engineering, and microbial ecology to create reproducible, scalable, and neuroactive bioproducts suitable for advanced nutritional and biotechnological applications (Kyei-Baffour et al., 2025; Rocchetti et al., 2025).

4 Conclusion:

Psychobiotic research has entered a transformative phase, shifting the focus from live probiotics to their metabolic and molecular by-products. Biogenic amines and other neuroactive metabolites now represent the biochemical basis through which gut microorganisms influence cognition, emotion and stress resilience in the host. The shift from evaluating cell viability to assessing functional metabolite efficacy has redefined microbial biotechnology, establishing postbiotics as reliable, consistent, and scalable tools for creating neuroactive and functional food systems. The intersection of microbial metabolism, food technology, and neurocognitive science suggests that engineered psychobiotic systems will play a pivotal role in promoting mental well-being and metabolic balance in the future.

Future advances will depend on linking metabolomic profiling with mechanistic understanding to optimise the production and application of these neuroactive compounds. Identifying metabolite signatures, clarifying host–microbe signalling pathways and applying precision fermentation and synthetic biology will enable the controlled production of specific psychobiotic molecules. Together, these developments will shift the focus from organism-based supplementation to molecule-driven functional biotics, thereby bridging the gap between microbial metabolism and human cognitive health within a reproducible and technologically sustainable framework.

References

1. Amobonye, A., Pillay, B., Hlope, F., Pillai, S.: Postbiotics: An insightful review of the latest category in functional biotics. World Journal of Microbiology and Biotechnology 41(3), 293 (2025)
2. Asokan, N., Kumar, P.: Microbial influences on neurotransmitters: Exploring the gut–brain axis and psychobiotic therapies. (2025)

3. Alagiakrishnan, K., Khan, S., Khanna, R.: Gut–brain axis modulation through probiotic interventions in aging populations: A clinical overview. Frontiers in Neuroscience 18, 1220435 (2024)
4. Barbosa, J.P., Martins Dala Paula, B., Souza, P.A.: Polyamines and their precursor produced by lactic acid bacteria and their concept as metabiotics. Food Reviews International 40(10), 3555–3571 (2024)
5. Bertollo, A.G., da Silva, H.T., Ferreira, L.K.: Hypothalamus–pituitary–adrenal and gut–brain axes in depression. Frontiers in Neuroscience 19, 1541075 (2025)
6. Bleibel, L., Dziomba, S., Waleron, K.F., Kowalczyk, E., Karbownik, M.S.: Deciphering psychobiotics' mechanism of action: Bacterial extracellular vesicles in the spotlight. Frontiers in Microbiology 14, 1211447 (2023)
7. Bleibel, L., Sokołowska, P., Henrykowska, G., Owczarek, J., Wiktorowska-Owczarek, A.: Unveiling the anti-inflammatory effects of antidepressants. Pharmaceuticals 18(6), 867 (2025)
8. Bravo, J.A., et al.: [Article details]. (2011)
9. Carthy, E., Ellender, T.: Histamine, neuroinflammation and neurodevelopment: A review. Frontiers in Neuroscience 15, 680214 (2021)
10. Chen, Y., Ho, C.-T., Zhang, X.: Regulatory mechanism of intermittent fasting and probiotics on cognitive function. Journal of Food Science 90(4), e70132 (2025)
11. Cryan, J.F., O'Riordan, K.J., Sandhu, K.V., Dinan, T.G.: The microbiota–gut–brain axis. Physiological Reviews (2019)
12. Cryan, J.F., O'Riordan, K.J., Sandhu, K.V., Dinan, T.G.: The microbiota–gut–brain axis. Physiological Reviews 101(4), 1689–1763 (2021)
13. Du, Q., et al.: Probiotics/prebiotics/synbiotics and neuropsychiatric outcomes: An umbrella review. Beneficial Microbes 15(6), 589–608 (2024)
14. Duan, Y., Li, Y., Wang, B.: Microbiota-derived metabolites modulate immune–brain communication. Cell Reports Medicine 4(11), 101145 (2023)
15. El Far, et al.: [Article details]. (2023)
16. Gomes, P.: Health potential of GABA-producing Lactococcus lactis strains. Doctoral dissertation, Institut National Polytechnique de Toulouse (2023)
17. Głowacka, P., Oszajca, K., Pudlarz, A., Szemraj, J., Witusik-Perkowska, M.: Postbiotics targeting aging brain pathways. Nutrients 16(14), 2244 (2024)
18. Hua, Q., Wong, C.H., Li, D.: Postbiotics enhance functional edible coatings for salmon fillets. Food Packaging and Shelf Life 34, 100954 (2022)
19. Hwang, Y.K., Oh, J.S.: Interaction of the vagus nerve and serotonin in the gut–brain axis. International Journal of Molecular Sciences 26(3), 1160 (2025)
20. Islam, F., et al.: Role of postbiotics in food and health: A comprehensive review. CyTA – Journal of Food 22(1), 2386412 (2024)
21. Jang, H.J., Lee, N.K., Paik, H.D.: Advance of probiotics to metabiotics. Journal of Microbiology and Biotechnology 34(3), 487 (2024)
22. Karukuvelraja, R., Saranya, N.: Exploring categorization of probiotics. Probiotics and Antimicrobial Proteins (2025)
23. Khan, I.M., et al.: The microbiota as a key regulator of physiology in mammals. Frontiers in Microbiology 15, 1480811 (2024)
24. Kyei-Baffour, V.O., et al.: Psychobiotics and the gut–brain axis. Critical Reviews in Food Science and Nutrition, 1–20 (2025)
25. LaGreca, M., Hutchinson, D.R., Skehan, L.: The microbiome and neurotransmitter activity. The Journal of Science and Medicine 3(2) (2021)

26. Lan, Y., Zhang, X., Wang, S.: SCFAs and enteroendocrine signaling. Frontiers in Nutrition 11, 1453172 (2024)
27. Liang, Y., Wang, Z., Qiao, Y.: Postbiotics targeting aging brain pathways. Journal of Neurochemistry 175(5), 755–770 (2025)
28. Mansuy-Aubert, V., Ravussin, Y.: Microbial metabolites and metabolic homeostasis. Annual Review of Nutrition 43, 257–279 (2023)
29. Marano, G., et al.: Gut microbiota in women and well-being. World Journal of Gastroenterology 29(45), 5945 (2023)
30. Margoob, M., Kouser, S., Jan, N.: Serotonin: The link between gut microbiome and brain. In: Serotonin–Neurotransmitter and Hormone of Brain, Bowels and Blood. IntechOpen (2024)
31. Merenstein, D., et al.: Emerging issues in probiotic safety. Gut Microbes 15(1), 2185034 (2023)
32. Mishra, B., et al.: Postbiotics in food preservation. Food Production, Processing and Nutrition 6(1), 28 (2024)
33. Mohammad, S., Thiemermann, C.: Metabolic endotoxemia and systemic inflammation. Frontiers in Immunology 11, 594150 (2021)
34. Moradi, M., et al.: Postbiotics produced by lactic acid bacteria. Comprehensive Reviews in Food Science and Food Safety 19(6), 3390–3415 (2020)
35. Nasri, F., Alizadeh, A., İncili, G.K., Moradi, M.: Chemical composition of Lactobacillus acidophilus postbiotics. Probiotics and Antimicrobial Proteins 16(2), 348–361 (2024)
36. Ortlek, B.E., Akan, Ö.B.: SCFA-driven vagus nerve signaling modeled via molecular communication. IEEE Transactions on Molecular, Biological and Multi-Scale Communications 10(2), 155–169 (2024)
37. Park, J.C., Chang, L., Kwon, H.K., Im, S.H.: Decoding the gut–immune–brain axis. Cellular & Molecular Immunology, 1–26 (2025)
38. Prajapati, N., et al.: Postbiotic production and microbial metabolites. Frontiers in Microbiology 14, 1306192 (2023)
39. Ramesh, V., Pandey, S., Thomas, P.: Probiotics modulating gut–brain axis for cognition. Frontiers in Pharmacology 15, 1348297 (2024)
40. Ranjha, M.M.A.N., et al.: Nutritional and health potential of probiotics. Applied Sciences 11(23), 11204 (2021)
41. Rocchetti, M.T., Capurso, G., Brunetti, L.: Psychobiotic properties of lactic acid bacteria. Journal of Microbiome Research 12(1), 47–59 (2025)
42. Rusch, B.D., Chen, L., Johnson, S.A.: Tryptophan metabolism and HPA modulation. Frontiers in Endocrinology 14, 1174581 (2023)
43. Salminen, S., et al.: ISAPP consensus on the definition and scope of postbiotics. Nature Reviews Gastroenterology & Hepatology 18(9), 649–667 (2021)
44. Schneider, E., O'Riordan, K.J., Clarke, G., Cryan, J.F.: Feeding gut microbes to nourish the brain. Nature Metabolism 6(8), 1454–1478 (2024)
45. Scott, E., De Paepe, K., Van de Wiele, T.: Postbiotics and health-modulatory biomolecules. Biomolecules 12(11), 1640 (2022)
46. Slykerman, R.F., et al.: Precision psychobiotics for gut–brain axis health. Microbial Biotechnology 18(1), e70079 (2025)
47. Śliwka, A., Polak-Berecka, M., Zdybel, K., Waśko, A.: Psychobiotics in depression: A systematic review. Nutrients 17(3), 2139 (2025a)
48. Śliwka, L., Kowalska, M., Krajewska, M.: Extracellular vesicles in psychobiotic mechanisms. Frontiers in Microbiology 16, 127905 (2025b)

49. Szydłowska, A., Sionek, B.: Probiotics and postbiotics affecting immune response. Microorganisms 11(1), 104 (2022)
50. Tian, P., et al.: Bifidobacterium breve reverses chronic stress-induced depression. Neurobiology of Stress 12, 100216 (2020)
51. Tillisch, K., et al.: Fermented milk product with probiotics modulates brain activity. Gastroenterology 144(7), 1394–1401 (2013)
52. Vinderola, G., Sanders, M.E., Salminen, S.: The concept of postbiotics. Foods 11(8), 1077 (2022)
53. Xin, Y., et al.: Immunomodulatory potential of L. helveticus postbiotics. Food Bioscience 61, 104842 (2024)
54. Yeşilyurt, N., Yılmaz, B., Ağagündüz, D., Capasso, R.: Involvement of probiotics and postbiotics in immune modulation. Biologics 1(2), 89–110 (2021)
55. Yılmaz, N., Özogul, F., Moradi, M., Fadiloglu, E.E., Šimat, V., Rocha, J.M.: Reduction of biogenic amines using postbiotics. Journal of Biotechnology 358, 118–127 (2022)
56. Zandifar, A., et al.: Effect of prebiotics/probiotics on mental health. Brain and Behavior 15(3), e70401 (2025)
57. Zhang, T., Zhao, C., Qiu, F.: SCFA-driven cytokine modulation. Frontiers in Immunology 14, 1190317 (2023)
58. Zhu, M., Li, Y., Chen, H., Hu, J.: Postbiotics: Formulation technologies and biological effects. Foods 14(13), 2358 (2025)