GRZELAK, Alicja. Microbiota and Mental Health: Decoding the Gut-Brain Axis. Quality in Sport. 2024;30:56737. eISSN 2450-3118.
https://dx.doi.org/10.12775/QS.2024.30.56737
https://apcz.umk.pl/QS/article/view/56737

The journal has been 20 points in the Ministry of Higher Education and Science of Poland parametric evaluation. Annex to the announcement of the Minister of Higher Education and Science of 05.01.2024. No. 32553.
Has a Journal's Unique Identifier: 201398. Scientific disciplines assigned: Economics and finance (Field of social sciences); Management and Quality Sciences (Field of social sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 r. Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398.
Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 06.12.2024. Revised: 15.12.2024. Accepted: 16.12.2024. Published: 16.12.2024.

Microbiota and Mental Health: Decoding the Gut-Brain Axis

Alicja Grzelak
Medical University of Lodz, al. Tadeusza Kościuszki 4, 90-419 Łódź
alagrzelak7@gmail.com
https://orcid.org/0009-0009-6951-6113

ABSTRACT

Introduction: The gut-brain axis, a bidirectional communication system between the gastrointestinal tract and the central nervous system, has garnered attention for its influence on mental health and neurological disorders. Central to this interaction is the gut microbiota, a diverse microbial community that regulates various physiological and psychological processes through neural, immune, and endocrine pathways.

Purpose of Work: This paper explores the role of the gut microbiota in shaping mental health and its potential involvement in neurological disorders. By systematically reviewing current

research, the study aims to provide a comprehensive understanding of microbial mechanisms influencing brain function and their implications for novel therapeutic interventions.

State of Knowledge: Evidence suggests that gut microbiota dysbiosis is associated with conditions such as anxiety, depression, autism spectrum disorders, and neurodegenerative diseases. Mechanistic insights reveal microbial production of neurotransmitters, modulation of the immune system, and regulation of the gut-brain barrier as pivotal factors. While preclinical studies and emerging clinical trials demonstrate promising outcomes, variability in study designs and individual microbiota profiles pose challenges.

Material and methods: The research methodology entailed a systematic review of the relevant literature, followed by a screening process to identify pertinent studies. The investigation encompassed a comprehensive search across scientific databases, including PubMed and Google Scholar.

Summary: The gut-brain axis highlights the intricate relationship between gut microbiota and brain health, offering a paradigm shift in understanding mental health and neurological diseases. Advances in microbiota-targeted therapies, including probiotics and dietary interventions, underscore its potential, though further research is needed to validate clinical efficacy and develop personalized treatment approaches.

Keywords: brain-gut axis; microbiota; mental health; probiotics; neurodegenerative diseases

INTRODUCTION

Definition and Scope

The gut-brain axis represents a bidirectional communication system between the gastrointestinal tract and the central nervous system. This complex axis involves the central nervous system, the enteric nervous system, the immune system, and the gut microbiota. Signals are transmitted between the gut and brain through various pathways, including the vagus nerve, hormones, and immune mechanisms [1]. These interactions influence a wide range of physiological and psychological processes, from digestion and immunity to mood and cognition. Critically, the gut microbiota play a key role in this axis, as they release metabolites and neurotransmitters that can impact brain function. Imbalances or dysbiosis in the gut microbiome have been associated with a number of physical and mental health disorders, such as anxiety, depression, and neurodevelopmental conditions. Elucidating the mechanisms of the gut-brain axis is essential for developing novel strategies to manage these prevalent and challenging health problems.

Relevance

Mental health issues and neurological conditions have become increasingly prevalent globally. Millions now suffer from conditions such as anxiety, depression, Parkinson's disease, and autism spectrum disorders. Traditional treatment methods have proven largely ineffective, leading researchers to explore new approaches. This has fueled significant interest in the role of gut microbiota within the scientific community. Studies have revealed associations between changes in gut bacteria and emotional as well as neurological problems. Specifically, imbalances in the gut microbiome, or dysbiosis, have been linked to heightened inflammation and altered brain signaling [2]. Consequently, targeting the gut-brain axis has emerged as a promising avenue for better understanding and managing these widespread health challenges.

Objective of the Review

The objective of this review is to provide a comprehensive summary of the current state of research on the gut-brain axis. It will examine key studies investigating the underlying mechanisms and therapeutic potential of the gut microbiome in influencing a wide range of

mental health conditions and neurodegenerative diseases. This exploration aims to develop a deeper understanding of how targeting the gut-brain axis can offer a promising and novel solution to address these prevalent and increasingly challenging global health challenges.

OVERVIEW OF THE BUT-BRAIN AXIS

Anatomical and Functional Aspects

The gut-brain axis represents a complex, bidirectional communication system between the gastrointestinal tract and the central nervous system. This multifaceted axis encompasses the immune system, gut microbiota, and enteric nervous system [3]. As defined by Mayer et al., signals are transmitted between the gut and brain through neurocrine, endocrine, and immune mechanisms, influencing a range of physiological and psychological processes, including emotional regulation, pain perception, and cognitive function. Importantly, the composition and metabolic activity of the gut microbiome have been shown to change in response to psychological or physical stress, which can in turn influence associated brain systems and emotional behaviors [3].

According to Sharon et al., gut microbiota play a crucial role in neurodevelopment and the central nervous system [4]. The researchers explain that the molecular signals from the gut microbiome influence key neurodevelopmental processes such as neurogenesis, myelination, and microglia maturation. These signals are particularly important during the pre- and postnatal stages when the brain needs to develop in a healthy and functional manner. Furthermore, the researchers highlight how the gut microbiota underpin the regulation of behaviors associated with anxiety, depression, and autism spectrum disorder. They also suggest that microbiota modulated by probiotics may have the potential to reprogram brain function. In essence, the gut microbiota are crucial in maintaining a balance between mental health and neurological disorders through their influence on the brain.

Key Mechanisms

The gut and brain communicate through various pathways. According to Sampson and Mazmanian, the vagus nerve is a crucial component of this bidirectional communication system, serving as a major conduit for signals traveling from the gut to the brain [5].

Additionally, microbial metabolites such as short-chain fatty acids act as essential mediators, influencing brain function and behavior [6]. Research by Needham, Kaddurah-Daouk, and Mazmanian further elucidates the role of microbial molecules in the gut-brain connection. Their work demonstrates how metabolites produced by gut bacteria can directly impact the central nervous system, potentially contributing to the development of mental health conditions and neurodegenerative diseases [6]. This complex interplay between the gut microbiome and the brain highlights the need for a deeper understanding of the mechanisms underlying the gut-brain axis. By unraveling these pathways, researchers may uncover promising new avenues for the prevention and treatment of various neurological and psychiatric disorders.

MENTAL HEALTH

Anxiety and Depression

The gut microbiome is intimately linked with various mental health disorders, including depression and anxiety [7]. As elucidated by Dinan and Cryan, the gut and brain communicate through diverse pathways, such as the vagus nerve, immune system, and microbial metabolites like short-chain fatty acids and tryptophan. Notably, the composition of gut microbiota differs among individuals with neuropsychiatric conditions. These microbial communities undergo dynamic changes throughout the lifespan, with factors like mode of birth (cesarean vs. vaginal) and aging in poor health contributing to reduced microbial diversity. These alterations in the gut microbiome may play a role in the development and progression of anxiety and depression. Cryan and Dinan have characterized the gut microbiome as 'mind-altering microorganisms' capable of modulating mood, cognition, and behavior [8]. They have elucidated how gut bacteria communicate with the central nervous system through neural, endocrine, and immune pathways. Notably, exposure to probiotics has been shown to alleviate anxiety-like behaviors, whereas the absence of gut microbiota in germ-free animal studies has been associated with increased anxiety [8]. These findings suggest that manipulating the gut microbiome may present a promising approach for treating anxiety and depression.

The research by Foster and Neufeld offers further evidence of the connection between gut microbiota and mental health. They demonstrate that stress-induced changes to the gut microbiome can subsequently impact stress-related behaviors. This is because certain bacteria in the gastrointestinal tract have the ability to activate signaling pathways within the central nervous system. Importantly, these pathways are differentially influenced by probiotic and

pathogenic bacteria, leading to divergent effects on mood and anxiety-related behaviors [9]. Understanding these underlying mechanisms could open up new avenues for successfully treating anxiety and depression by targeting the gut microbiome.

Stress Response

Gut microbiota have been shown to significantly influence stress responses. Sudo et al. investigated the impacts of gut microbiota on the hypothalamic-pituitary-adrenal axis, which regulates the body's stress response [10]. Their study compared germ-free mice to specific pathogen-free mice and found that under restraint stress, the germ-free mice displayed exaggerated stress responses, characterized by increased levels of corticosterone and adrenocorticotropic hormone. However, colonization of the mice with Bifidobacterium infantis eliminated these effects. This research demonstrates that the presence of gut microbiota during early life is necessary for appropriate stress regulation later in life [10].

Bravo et al. examined the influence of specific probiotics on stress responses [11]. They investigated the effects of Lactobacillus rhamnosus on GABA receptor regulation in various brain regions. GABA is a critical inhibitory neurotransmitter that plays a pivotal role in modulating stress and mood. The researchers found that L. rhamnosus treatment reduced anxiety- and depression-related behaviors in mice, along with lowering corticosterone levels during stress. Notably, these beneficial effects were absent in mice with severed vagus nerves, underscoring the vital role of the vagus nerve as a communication pathway between the gut and brain [11].

NEUROLOGICAL DISORDERS

Autism Spectrum Disorders (ASD)

Research has established that neurodevelopmental disorders like autism spectrum disorders are significantly influenced by the gut microbiome. Hsiao et al. observed that individuals with ASD frequently exhibit gastrointestinal abnormalities, which can also impact their behavior and cognition. In a study using a maternal immune activation mouse model, the researchers demonstrated that these mice displayed gut barrier defects and alterations in microbial

composition. This was accompanied by anxiety-like behavior, communication deficits, and repetitive actions. Notably, treatment with Bacteroides fragilis, a common gut bacterium, enhanced gut barrier integrity and modified the microbial diversity in these MIA mice. Furthermore, this intervention ameliorated the behavioral abnormalities, underscoring the powerful causal relationship between the gut microbiome and the symptoms of ASD. The researchers also detected altered serum metabolomic profiles in the MIA offspring, and exposure of naive mice to the same increased metabolites elicited similar behavioral changes. These findings suggest that the gut microbiome plays a critical role in ASD through its impact on the host metabolome, ultimately affecting brain function and behavior [12].

Hoban et al.'s research further underscored the crucial role of gut microbiota in early neurodevelopment [13]. Their study found that germ-free mice lacking gut microbiota exhibited aberrant brain function and behavior. Furthermore, chronic antibiotic administration in adult rodents impaired spatial memory and increased depressive-like conduct. Alterations in serotonin levels and brain-derived neurotrophic factor expression corroborated the potential contribution of gut microbiota to the healthy communication between the gastrointestinal system and the brain. These findings suggest that disruption of the gut microbiome can influence neurological outcomes, particularly in neurodevelopmental disorders like autism spectrum disorder.

Parkinson’s Disease

Parkinson's disease is another neurological disorder associated with disruptions in gut microbiota. Sampson et al. found that mice overexpressing the Parkinson's-linked protein α-synuclein exhibited motor deficits, microglial activation, and α-synuclein pathology, all of which were dependent on the presence of gut microbiota [14]. Specifically, microbial metabolites were shown to promote neuroinflammation and motor dysfunction, as evidenced by reduced motor impairment in germ-free mice overexpressing α-synuclein compared to those colonized with gut bacteria. Furthermore, antibiotic treatment ameliorated these motor impairments, which were then restored upon reintroduction of specific microbiota. Importantly, mice colonized with gut microbiota from Parkinson's patients exhibited more severe motor deficits than those colonized with microbiota from healthy individuals. These findings suggest that gut dysbiosis, an imbalance in microbial populations, may contribute to Parkinson's disease as a risk factor by influencing neuroinflammation and motor symptoms. Additionally, Sampson

et al. proposed that the establishment of gut-brain signaling pathways after birth plays a crucial role in the development of neurodegenerative disorders like Parkinson's disease [14].

Alzheimer's Disease

There is also evidence suggesting a role for gut microbiota in Alzheimer's disease, a neurodegenerative disorder characterized by cognitive impairment. Clarke et al. examined how early-life programming by the gut microbiome influences central nervous system signaling. Their findings indicate that germ-free animals exhibited elevated hippocampal serotonin levels and altered neurodevelopmental outcomes. Furthermore, long-term changes in serotonergic neurotransmission following early-life disruption of the gut microbiome could not be fully reversed by subsequent microbial colonization. These results demonstrate that the gut microbiota plays a pivotal role in the development and regulation of the central nervous system, particularly in serotonergic pathways. However, disruptions to the microbiome during critical developmental periods may heighten the risk of cognitive decline and neurodegeneration in adulthood [15].

Cheung et al.'s systematic review revealed that individuals with major depressive disorder who are at risk of Alzheimer's disease exhibited significant differences in their gut microbial composition compared to healthy controls [16]. Specifically, certain microbial taxa, such as the Lachnospiraceae family, were either elevated or reduced in the affected population. While individual studies displayed variability, these findings suggest that an imbalance in gut microbiota, or gut dysbiosis, may be linked to cognitive impairment through the metabolic activities of the microbiome [16].

INTERVENTIONS

Probiotics and Prebiotics

Probiotics and prebiotics are considered valuable tools for modulating the gut–brain axis. Bravo et al. examined the effects of the probiotic Lactobacillus rhamnosus on emotional regulation and neurotransmitter expression, observing that chronic treatment with L. rhamnosus altered GABA receptor expression in different regions of the brain, including increased cortical GABA mRNA and reduced levels in the hippocampus and amygdala. Additionally, Kelly et al.

investigated the ability of gut microbiota to influence neurobehavioral modulation, demonstrating that fecal microbiota transplantation from depressed patients into microbiota-deficient rats resulted in depressive-like behavior and anxiety in the recipient animals, thereby providing a causal relationship between gut microbiota and mood disorders. These findings suggest that probiotics and microbiota-targeted therapies may serve as dietary interventions for conditions such as anxiety and depression [17].

Dietary Modifications

Dietary changes can significantly alter the composition and function of the gut microbiota, subsequently influencing the gut–brain axis. De Palma et al. explored how dietary shifts affect the microbiome and impact anxiety as well as irritable bowel syndrome. Their study involved transplanting fecal microbiota from IBS patients with diarrhea into germ-free mice. The results showed that the recipient mice exhibited increased gastrointestinal transit, intestinal barrier dysfunction, and anxiety-like behaviors [18]. These findings suggest that specific dietary components upon which the microbiota relies may contribute to the behavioral and intestinal symptoms observed in IBS.

Gareau et al. investigated the potential of dietary interventions involving probiotics to prevent stress-induced memory deficits. In their study, mice were infected with Citrobacter rodentium and subjected to acute stress, which led to memory dysfunction in the infected animals. However, when the mice received daily probiotic treatment, their behavior was normalized, and the memory impairments were prevented [19]. This research demonstrates how modulating the gut microbiome through dietary modifications can play a role in managing stress-related cognitive and behavioral issues.

Fecal Microbiota Transplantation (FMT)

Fecal microbiota transplantation has emerged as a promising intervention to alter gut microbiota and address related disorders. De Palma et al. investigated the effects of FMT in irritable bowel syndrome patients, revealing that transferring fecal microbiota from healthy donors to IBS-D (diarrhea-predominant IBS) patients can improve gut function and reduce behavioral symptoms [20]. Furthermore, mice transplanted with microbiota from IBS-D patients exhibited changes in serum metabolomic profiles and immune activation, confirming the impact of gut microbiota

on intestinal and behavioral health. Mangiola et al. explored the potential role of FMT in autism and mood disorders, and found that gut microbiota dysbiosis occurs during the development of these conditions. While FMT has primarily been studied in experimental settings, the available evidence suggests that therapeutic modulation of the gut microbiome may be beneficial for treating disorders such as autism and major depressive disorder.

CHALLENGES

Knowledge Gaps

Although the gut-brain axis is now more widely recognized, significant knowledge gaps persist. Vuong et al. have discussed the complexity of host-microbiome interactions and the limited understanding of the mechanisms linking gut microbiota to neurophysiology and behavior. However, the causal pathways between microbial changes and neurological outcomes remain unclear [21].

Additional research is needed to elucidate how gut microbiota may modulate social, stress-induced, and cognitive behaviors, particularly the role of specific microbial species and their effects on brain regions such as the hippocampus and amygdala. The relationship between stress and gut microbiota, and its impact, is another critical area for further investigation. While studies have demonstrated the association between gut dysbiosis and neurobehavioral disorders like major depression, the detailed mechanisms by which stress-induced microbial changes may contribute to mental health conditions are not well-understood. Addressing these knowledge gaps is essential to develop targeted interventions for stress-induced mental health disorders.

Future Research

Future research on the gut-brain axis should aim to inform the development of personalized interventions that can effectively target it. Feng et al. found that gut microbiota significantly influence the efficacy and toxicity of drugs, with considerable individual variation [22]. Personalizing the manipulation of gut microbiota may thus represent a promising strategy to optimize drug effects and minimize adverse reactions through targeted medical treatment. According to Rogers et al., microbiota-directed therapies must gain wider acceptance in mainstream healthcare. They describe how the gut microbiome influences neural development,

learning, and behavior. Changes in gut microbial composition have succeeded in reversing depressive-like behaviors in animal models.

Further research is needed to identify the specific microbial strains or metabolites responsible for these effects, in order to design targeted microbiota-based therapies. Additionally, the animal-based findings must be validated through longitudinal human studies to facilitate their clinical translation [23].

Potential Applications

Research on the gut microbiome has promising applications for developing therapies for neurological and mental health conditions. Studies by Molska et al. have demonstrated that gut microbiota regulate the levels of brain-derived neurotrophic factor and neurogenesis, which are crucial for brain health [24]. Although reduced BDNF levels are often observed in dysbiosis, they are associated with cognitive impairment and mood disorders. Furthermore, lifestyle interventions such as regular exercise and certain probiotics or prebiotics have been shown to increase BDNF levels and promote overall mental well-being [24].

In addition, microbiota-targeted therapies may provide a novel treatment strategy for conditions like depression, autism, and Alzheimer's disease. To develop such therapies, it will be necessary to identify the key microbial strains involved and understand their interactions with the nervous system.

CONCLUSIONS

The gut-brain axis is a dynamic communication system that connects the gut and the brain through the nervous, immune, and endocrine systems. This interaction is crucial, as gut microbiota influence mental health and neurological disorders, including anxiety, depression, autism, Parkinson's, and Alzheimer's disease. Imbalanced gut microbiota have been linked to inflammation, altered brain signaling, and behavioral changes. Interventions such as probiotics, dietary modifications, and fecal microbiota transplantation offer promise for addressing these challenges. These approaches have demonstrated the ability to modulate gut-brain communication and improve mental and neurological health outcomes.

However, further research is necessary to translate these findings into clinical practice. Future studies should focus on elucidating the underlying mechanisms of microbiota interactions and

developing personalized approaches. Advancing this field can lead to innovative therapies aimed at enhancing the quality of life for individuals with mental and neurological disorders.

DISCLOSURE

Authors contribution:

Conceptualization: Alicja Grzelak

Methodology: Alicja Grzelak

Software: Alicja Grzelak

Check: Alicja Grzelak

Formal Analysis: Alicja Grzelak

Investigation: Alicja Grzelak

Resources: Alicja Grzelak

Data Curation: Alicja Grzelak

Writing-Rough Preparation: Alicja Grzelak

Writing-Review and Editing: Alicja Grzelak

Visualization: Alicja Grzelak

Supervision: Alicja Grzelak

Project Administration: Alicja Grzelak

The author has read and agreed with the published version of the manuscript.

Funding Statement: The Study Did Not Receive Special Funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Conflict Of Interest: The author declares no conflict of interest.

REFERENCES

[1] M. Carabotti, A. Scirocco, M. A. Maselli, and C. Severi, “The gut-brain axis: interactions between enteric microbiota, central and enteric nervous systems.,” Apr. 02, 2015, National Institutes of Health. Accessed: Dec. 2024. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/25830558

[2] M. Kandpal et al., “Dysbiosis of Gut Microbiota from the Perspective of the Gut–Brain Axis: Role in the Provocation of Neurological Disorders,” Nov. 03, 2022, Multidisciplinary Digital Publishing Institute. doi: 10.3390/metabo12111064.

[3] E. A. Mayer, R. Knight, S. K. Mazmanian, J. F. Cryan, and K. Tillisch, “Gut Microbes and the Brain: Paradigm Shift in Neuroscience,” Nov. 12, 2014, Society for Neuroscience. doi: 10.1523/jneurosci.3299-14.2014.

[4] G. Sharon, T. R. Sampson, D. H. Geschwind, and S. K. Mazmanian, “The Central Nervous System and the Gut Microbiome,” Nov. 01, 2016, Cell Press. doi: 10.1016/j.cell.2016.10.027.

[5] T. R. Sampson and S. K. Mazmanian, “Control of Brain Development, Function, and Behavior by the Microbiome,” May 01, 2015, Cell Press. doi: 10.1016/j.chom.2015.04.011.

[6] B. D. Needham, R. Kaddurah-Daouk, and S. K. Mazmanian, “Gut microbial molecules in behavioural and neurodegenerative conditions,” Oct. 16, 2020, Nature Portfolio. doi: 10.1038/s41583-020-00381-0.

[7] T. G. Dinan and J. F. Cryan, “The impact of gut microbiota on brain and behaviour,” Sep. 12, 2015, Lippincott Williams & Wilkins. doi: 10.1097/mco.0000000000000221.

[8] J. F. Cryan and T. G. Dinan, “Mind-altering microorganisms: the impact of the gut microbiota on brain and behaviour,” Sep. 12, 2012, Nature Portfolio. doi: 10.1038/nrn3346.

[9] J. A. Foster and K. M. Neufeld, “Gut–brain axis: how the microbiome influences anxiety and depression,” Feb. 04, 2013, Elsevier BV. doi: 10.1016/j.tins.2013.01.005.

[10] N. Sudo et al., “Postnatal microbial colonization programs the hypothalamic–pituitary–adrenal system for stress response in mice,” May 11, 2004, Wiley. doi: 10.1113/jphysiol.2004.063388.

[11] J. A. Bravo et al., “Ingestion of Lactobacillus strain regulates emotional behavior and central GABA receptor expression in a mouse via the vagus nerve,” Aug. 29, 2011, National Academy of Sciences. doi: 10.1073/pnas.1102999108.

[12] E. Y. Hsiao et al., “Microbiota Modulate Behavioral and Physiological Abnormalities Associated with Neurodevelopmental Disorders,” Dec. 01, 2013, Cell Press. doi: 10.1016/j.cell.2013.11.024.

[13] A. E. Hoban et al., “Behavioural and neurochemical consequences of chronic gut microbiota depletion during adulthood in the rat,” Oct. 15, 2016, Elsevier BV. doi: 10.1016/j.neuroscience.2016.10.003.

[14] T. R. Sampson et al., “Gut Microbiota Regulate Motor Deficits and Neuroinflammation in a Model of Parkinson’s Disease,” Dec. 01, 2016, Cell Press. doi: 10.1016/j.cell.2016.11.018.

[15] G. Clarke et al., “The microbiome-gut-brain axis during early life regulates the hippocampal serotonergic system in a sex-dependent manner,” Jun. 12, 2012, Springer Nature. doi: 10.1038/mp.2012.77.

[16] S. G. Cheung, A. Goldenthal, A. Uhlemann, J. J. Mann, J. M. Miller, and M. E. Sublette, “Systematic Review of Gut Microbiota and Major Depression,” Feb. 11, 2019, Frontiers Media. doi: 10.3389/fpsyt.2019.00034.

[17] J. R. Kelly et al., “Transferring the blues: Depression-associated gut microbiota induces neurobehavioural changes in the rat,” Jul. 26, 2016, Elsevier BV. doi: 10.1016/j.jpsychires.2016.07.019.

[18] G. D. Palma et al., “Transplantation of fecal microbiota from patients with irritable bowel syndrome alters gut function and behavior in recipient mice,” Mar. 01, 2017, American Association for the Advancement of Science. doi: 10.1126/scitranslmed.aaf6397.

[19] M. G. Gareau et al., “Bacterial infection causes stress-induced memory dysfunction in mice,” Oct. 21, 2010, BMJ. doi: 10.1136/gut.2009.202515.

[20] F. Mangiola, “Gut microbiota in autism and mood disorders,” Dec. 31, 2015, Baishideng Publishing Group. doi: 10.3748/wjg.v22.i1.361.

[21] H. E. Vuong, J. M. Yano, T. C. Fung, and E. Y. Hsiao, “The Microbiome and Host Behavior,” Mar. 16, 2017, Annual Reviews. doi: 10.1146/annurev-neuro-072116-031347.

[22] G. B. Rogers, D. J. Keating, R. L. Young, M. Wong, J. Licinio, and S. Wesselingh, “From gut dysbiosis to altered brain function and mental illness: mechanisms and pathways,” Apr. 19, 2016, Springer Nature. doi: 10.1038/mp.2016.50.

[23] W. Feng, J. Liu, H. Ao, S. Yue, and C. Peng, “Targeting gut microbiota for precision medicine: Focusing on the efficacy and toxicity of drugs,” Jan. 01, 2020, Ivyspring International Publisher. doi: 10.7150/thno.47289.

[24] M. Molska et al., “The Influence of Intestinal Microbiota on BDNF Levels,” Aug. 29, 2024, Multidisciplinary Digital Publishing Institute. doi: 10.3390/nu16172891.