Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 32s (2025)
https://www.jneonatalsurg.com

OPEN ACCESS

Human Gut Microbiota Dysbiosis on Pesticides Exposure

Neha Sagar[1], Sisir Nandi[*2]

[1,*2]Global Institute of Pharmaceutical Education and Research (GIPER), Affiliated to Veer Madho Singh Bhandari Uttarakhand Technical University), Kashipur-244713, Uttarakhand, India

[*]**Corresponding author:**

Prof. (Dr.) Sisir Nandi

Email ID: sisir.iicb@gmail.com

Cite this paper as: Neha Sagar, Sisir Nandi, (2025) Human Gut Microbiota Dysbiosis on Pesticides Exposure. *Journal of Neonatal Surgery*, 14 (32s), 2780-2787.

ABSTRACT

The gut microbiome refers to the vast community of microorganisms—mainly bacteria, but also viruses, fungi, archaea, and protozoa—that inhabit the digestive tract, primarily the intestines. These microbes form a complex ecosystem that interacts with our body, influencing digestion, metabolism, immune function, and even aspects of mental health. Dysbiosis means the loss of balance. The gut microbiota dysbiosis happens with their loss due to creating negative environment. It happens with many reasons. One of the major causes of gut microbiota dysbiosis is exposure on pesticides used in the fields. The pesticides in agricultural practices have raised concerns about its potential health effects on humans. This study explores the intricate relationship between pesticide exposure and its detrimental impact on the gastrointestinal microbiome.

Keywords: *Gut microbiota, Dysbiosis, Pesticide exposure, GIT issues*

1. INTRODUCTION

The gastrointestinal tract of human digestive system hosts a vast community of tiny living organisms known as microorganisms, collectively referred to as the gut microbiota. These microbes include bacteria, viruses, fungi, protozoa archaea, and other microscopic entities that play a vital role in supporting human health [1]. Gut microbiota provides numerous essential benefits to the human body. These strengthen the gut wall and shape the intestinal lining [2]. They produce energy from food and assists in digestion [3]. They protect the body from harmful pathogens and germs [4]. They regulate the immune system, helping the body detect and respond to threats appropriately, maintains metabolic balance and overall homeostasis in the immune system [5]. When the composition of the gut microbiota becomes disrupted — a condition known as dysbiosis which weaken immune defense mechanisms, increase the risk of infections and inflammatory disorders, lead to broader health complications like inflammatory bowel disease (IBD) [5,6]. The health significance of the gut has been acknowledged for centuries. As far back as 400 B.C., Hippocrates declared, *"Death begins in the gut."* Modern research confirms that the gut microbiota is closely linked to both maintaining health and contributing to the development of various diseases [1,6]. Dysbiosis has been associated with a wide range of chronic human health conditions, including mental health disorders (anxiety, depression), cardiovascular diseases (high blood pressure, heart disease), metabolic disorders (obesity, diabetes), digestive diseases (inflammatory bowel disorders), and even some forms of cancer [7].

The composition and diversity of an individual's gut microbiota are influenced by many host-related factors, including diet (the most influential factor), lifestyle, age, environmental exposure [8]. In individuals at high risk for disease, alterations in gut bacteria can impair immune function and increase the likelihood of inflammatory diseases like IBD. Therefore, restoring microbial balance is seen as a promising therapeutic approach to managing such disorders [9].

Various roles of gut microbiota

The gut microbiome refers to the largest community of microorganisms residing in the human gastrointestinal (GI) tract. These include bacteria, viruses, fungi, archaea (organisms similar to bacteria but with distinct molecular traits), and protozoa [10]. These tiny microorganisms, collectively known as the human gut microbiota, usually live in a cooperative (symbiotic) relationship with the human body both sides benefit. They help protect against harmful bacteria, assist in nutrient processing, and support various bodily functions [11]. The gut microbiota plays numerous crucial roles, including metabolizing nutrients, breaking down drugs and harmful chemicals, regulating the immune system, defending the body from pathogens and maintaining homeostasis by producing essential metabolites [12]. Gut microbiota also influences how the body processes food and energy, which is particularly important as metabolic disorders like obesity and related health issues are becoming more prevalent [13]. A balanced gut microbiota is essential for the central nervous system (CNS) to function properly. An imbalance known as dysbiosis can lead to brain inflammation, contributing to mental health disorders like anxiety and depression. The gut microbiota is a key regulator in the two-way communication between the gut and the brain, often referred to as the gut-brain axis [14]. Experiments involving germ-free mice and probiotic trials in humans have shown that gut microbiota affects not only mental health but also gastrointestinal disorders such as Irritable Bowel Syndrome (IBS), and Inflammatory Bowel Disease (IBD) [15]. Certain microbial species may be especially important in mental health. These include Phyla *Firmicutes*, *Actinobacteria* Genera: *Bacteroides*, *Bifidobacterium.* These microbes are being studied for their roles in regulating mood, inflammation, and metabolism [16].

Gut dysbiosis

The term gut dysbiosis describes a disruption in the normal gut microbial balance, typically seen as fewer beneficial species, greater numbers of pathogenic bacteria, or decreased overall microbial variety dysbiosis interferes with essential metabolic and immune activities typically associated with a balanced and healthy gut microbiota [17]. Gut dysbiosis can result from a variety of contributing factors, both internal and external. The broad-spectrum antibiotics, particularly 6-aminopenicilanic acid such as amoxicillin, 6-aminocephalosporanic acid such as cefixime, and fluoroquinolones like norfloxacin, ciprofloxacin and azalide such as clarithromycin, can significantly inhibit the gut microbiota sometimes for months or even years thereby elevating the risk of gastrointestinal issues like loose motion, constipation, gastritis, obesity, allergic reactions, and asthma. Additionally, numerous pharmaceuticals including proton pump inhibitors (PPIs), nonsteroidal anti-inflammatory drugs (NSAIDs), antidepressants, antipsychotics, opioids, and statins are known to alter the composition and diversity of intestinal microbes [18]. Dietary bad habits of intake of low in fiber diets, high in fat or sugar, sweets, chili, spicy, fried foods, night awakening, insufficient sleep, chronic stress, smoking, and alcohol intake, all contribute to reduced microbial diversity and promote the proliferation of pro-inflammatory bacterial species [19]. Both acute and chronic infections of the gastrointestinal tract, alongside conditions like small intestinal bacterial overgrowth and other inflammatory disorders, can disrupt microbial balance [20]. The genetic predispositions such as single nucleotide polymorphisms in genes like LCT as well as environmental exposures during early development and increasing urbanization have been shown to shape and influence gut microbial communities [21]. Gut dysbiosis is increasingly recognized as a contributor to immune system imbalance, where disruptions in microbial equilibrium can elevate pro-inflammatory taxa while diminishing populations that mediate anti-inflammatory effects [22]. This immune dysregulation often coincides with intestinal barrier dysfunction, as the depletion of beneficial microbial by-products—such as short-chain fatty acids (SCFAs)—compromises mucosal integrity, allowing endotoxins and microbial products to translocate across the epithelium [23]. Furthermore, dysbiosis leads to metabolic derangements, including altered energy extraction, bile acid modification, and disrupted hormonal signaling, which collectively fuel conditions such as obesity and metabolic syndrome [24]. The gut microbiota also influences the gut–brain axis, modulating neurotransmitters like serotonin and gamma-aminobutyric acid (GABA), thereby impacting mood, cognition, and behavior [25]. In terms of diagnosis, clinical evaluation typically relies on symptomatology, encompassing gastrointestinal and systemic signs, along with tests such as stool analysis and breath tests for conditions like small intestinal bacterial overgrowth [26]. More sophisticated diagnostic tools include microbiome profiling through sequencing technologies, yielding dysbiosis indexes, although their routine clinical use remains under development [27]. Management strategies for dysbiosis emphasize dietary interventions, including fiber-rich, plant-based diets abundant in prebiotics and fermented foods, which help re-establish microbial diversity.

2. PESTICIDE EXPOSURE

Chronic exposure to pesticides whether through diet, water, or environmental contact introduces xenobiotic compounds that can significantly influence host physiology and disrupt gut microbial homeostasis. These chemicals (e.g., organophosphates, herbicides, insecticides) are linked to a range of health outcomes, from immune dysregulation and metabolic disturbances to neurological effects [28-29]. Recent studies highlight that pesticide exposure disrupts gut microbiota, which functions like a secondary endocrine system regulating immunity and hormones. Such disruption is linked to diseases like obesity, colon cancer, and diabetes. This review explores how pesticides alter gut microbes and their metabolites, impacting host health and metabolic functions [30]. Pesticides are chemicals used to control pests and weeds in agriculture. Various pesticides used in agricultural fields are used on vegetables, wheat, rice, etc in the fields to prevent insect infection and disease carriers. The increase in rate of population greatly demands an increase in food production [31].

The pests and insects attack the crops in the fields and loss the productivity. Without the use of pesticides, there would be a 78% loss of fruit production, a 54% loss of vegetable production, and a 32% loss of cereal production. Therefore, pesticides play a critical role in reducing diseases and increasing crop yields worldwide [32]. Their widespread use raises concerns about their impact on the environment and human health. Once sprayed, pesticides are volatilized and can be carried on air currents away from the treated surface. The volatilization is increased by the high vapor pressure, higher temperature, low relative humidity, and more open-air circulation in the field [33]. Pesticides are chemicals used to protect plants and people from pests, diseases, and weeds. They include insect killers, fungus killers, weed killers, rat poisons, and plant growth regulators. They are commonly used in farming and public health programs to prevent diseases like malaria and dengue fever. They are also used in public green spaces, sports fields, pet shampoos, building materials, and on boat bottoms to prevent unwanted species. Pesticides can cause health and environmental problems. Some pesticides have been banned in farming due to these issues. People can be exposed to pesticides through skin contact, eating, or breathing them in. The degree of harm depends on the type of pesticide used, how long and how one is exposed, and the individual's health. Pesticides can be broken down, excreted, stored, or build up in body fat. They can cause various health issues, including skin, stomach, nerve, cancer, breathing, reproductive, and hormone problems. High exposure can lead to hospitalization and death. Pesticide residues can be found in everyday foods and drinks, such as cooked meals, water, wine, fruit juices, and animal feeds. Washing and peeling may not completely remove these residues. Although most concentrations are within safe limits set by law, these limits might underestimate the real risk, especially when exposed to multiple chemicals simultaneously. Pesticide residues have also been found in breast milk, raising concerns about effects on unborn babies and children. The exposure to these pesticides may be linked to cardiovascular diseases, male reproductive issues, nervous system problems, dementia, and an increased risk of non-Hodgkin's lymphoma. Prenatal exposure has also been associated with shorter pregnancy duration and neurological issues in children. In which stresses the urgent need to significantly reduce the use of chemical pesticides in agriculture. It focuses on the chronic health effects of common pesticides, such as organochlorines, organophosphate, carbamates, pyrethroids, triazines, and neonicotinoids. It particularly highlights the health risks associated with glyphosate, a widely used herbicide in agriculture, showing the need for alternative solutions [34].

Gut Alteration

The human gut microbiota plays a vital role in maintaining host homeostasis, immune regulation, and metabolic functions. This complex ecosystem is highly sensitive to environmental pollutants, particularly pesticides, which can disrupt microbial diversity and functionality [35]. Pesticides, including organophosphates, pyrethroids, and carbamates, often accumulate in the human body through contaminated food and water sources, exerting unintended toxic effects on the gut microbial community [36]. These xenobiotics are increasingly recognized as non-target agents that perturb the composition and activity of gut microbiota, thereby contributing to a range of chronic diseases [37].

Pesticide-induced dysbiosis alters the balance between beneficial and pathogenic microbes, often reducing the abundance of commensal bacteria such as *Lactobacillus* and *Bifidobacterium*, while promoting the growth of pro-inflammatory taxa like *Proteobacteria* [38]. These shifts can impair gut barrier integrity, increase permeability, and trigger systemic inflammation commonly known as "leaky gut" which has been linked to the onset of metabolic syndrome, neurodegeneration, and autoimmune conditions [39]. Additionally, chronic exposure to glyphosate, one of the most widely used herbicides, has been shown to interfere with the shikimate pathway in gut bacteria, indirectly affecting host amino acid metabolism [40].

The gut microbiota also serves as a secondary endocrine organ by producing neurotransmitters, short-chain fatty acids, and other metabolites essential for host signaling pathways. Disruption of this metabolite network by pesticides can impair energy metabolism, modulate insulin signaling, and increase oxidative stress [41]. Emerging evidence suggests that pesticide-exposed microbiota release altered microbial metabolites that may mimic, enhance, or inhibit host hormonal activity, thus influencing endocrine and immune responses [42]. Such disruptions are particularly concerning in vulnerable populations like infants, pregnant women, and immunocompromised individuals. The studies have identified links between pesticide-driven gut alterations and increased risk for colorectal cancer, obesity, and type 2 diabetes [43]. Persistent organic pollutants like DDT and PCBs, even at low doses, are capable of altering microbial composition and increasing the production of endotoxins and lipopolysaccharides, both known to activate toll-like receptor pathways and contribute to low-grade chronic inflammation [44].

3. GUT MICROBIOTA–BLOOD–BRAIN BARRIER AXIS

The human gut microbiota, comprising trillions of microorganisms, plays a pivotal role beyond digestion contributing significantly to neural development and central nervous system (CNS) regulation through the gut–brain axis. One critical component of this axis is the blood–brain barrier (BBB), a selective barrier that shields the brain from harmful substances. Recent research indicates that gut microbiota can modulate the integrity and function of the BBB through various mechanisms, including immune signaling, microbial metabolites, and neuroactive compounds [45]. Alterations in gut microbiota composition, known as dysbiosis, can compromise BBB permeability, increasing the risk of neuroinflammation and neurological disorders [46]. Short-chain fatty acids (SCFAs)—particularly acetate, propionate, and butyrate—are microbial metabolites produced through the fermentation of dietary fiber. These SCFAs are essential in maintaining BBB tight junction proteins like occludin and claudin-5, which are critical for barrier integrity [47] In humans, a decreased abundance of SCFA-producing bacteria such as *Faecalibacterium prausnitzii* and *Roseburia* has been observed in neurodegenerative conditions like Alzheimer's and Parkinson's disease [48]. Another key mechanism is the regulation of systemic inflammation. Dysbiotic gut microbiota can lead to elevated levels of endotoxins like lipopolysaccharides (LPS), which enter circulation and induce systemic inflammation. These proinflammatory signals can reach the brain and disrupt the BBB by activating microglia and astrocytes, contributing to cognitive decline and mental health disorders [49] Tryptophan metabolism by gut microbes generates neuroactive metabolites such as kynurenine and indole derivatives, which can cross the BBB and influence neurotransmitter balance, impacting mood and behavior [50]. Evidence also supports the bidirectional nature of the gut microbiota–BBB axis. CNS disorders such as depression, autism spectrum disorder, and multiple sclerosis are often associated with altered gut microbiota profiles [51]. Conversely, experimental restoration of healthy gut microbiota through probiotics or fecal microbiota transplantation has shown potential in restoring BBB integrity and improving cognitive function in animal models [52]. These findings highlight a promising therapeutic window for targeting the gut microbiota in preventing or treating neurological diseases linked to BBB dysfunction.

4. GUT MICROBIOTA–BRAIN AXIS

The **gut microbiota–brain axis** is a bidirectional communication network involving microbial, neural, endocrine, and immune signaling between the gastrointestinal tract and central nervous system [53]. Gut microbiota produce neuroactive compounds such as serotonin, gamma-aminobutyric acid (GABA), and short-chain fatty acids (SCFAs), which influence brain development and behavior [54]. Pesticide-induced dysbiosis disrupts the production of these neurochemicals, leading to impaired neurodevelopment and emotional regulation [55]. Evidence from murine studies demonstrates that early-life exposure to chlorpyrifos alters gut microbiota and induces anxiety-like behaviors [56] These behavioral changes are accompanied by shifts in microbial communities, especially reductions in Lactobacillus and Bifidobacterium species [57]. Pesticide exposure increases intestinal permeability or "leaky gut," allowing lipopolysaccharides and other microbial toxins to enter systemic circulation [58]. This translocation triggers immune responses and promotes systemic inflammation, which can impair the blood–brain barrier (BBB) [59]. Compromised BBB allows proinflammatory cytokines to infiltrate the brain, aggravating neuroinflammation and neurodegeneration [60]. Pesticide-altered gut microbiota further reduces SCFA production, which normally helps maintain BBB integrity [47].

Thus, dysbiosis acts as a central player in connecting gut dysfunction with neural damage under pesticide stress [61]. The vagus nerve is a key pathway through which gut microbiota communicate with the brain, influencing mood and cognition [62]. Microbial imbalance caused by pesticides disrupts vagal signaling, impairing feedback loops that regulate stress and emotional behavior [63]. Additionally, alterations in microbial metabolites impact the hypothalamic–pituitary–adrenal (HPA) axis, intensifying stress responses [64]. These changes may contribute to neurobehavioral disorders such as depression, anxiety, and cognitive dysfunction [65].

Hence, the gut microbiota–brain axis represents a critical target of neurotoxicity in chronic pesticide exposure [66]. Neuroinflammatory changes following pesticide-induced dysbiosis are also linked to microglial activation in the brain [67]. Microglia, the CNS-resident immune cells, become activated in response to gut-derived cytokines and metabolites altered by dysbiosis [59] Prolonged microglial activation has been implicated in neurodevelopmental and neurodegenerative conditions, including autism and Parkinson's disease [68]. Glyphosate-based herbicides reduce beneficial bacterial species, further enhancing neuroinflammatory profiles [69]. These disruptions underscore the sensitivity of the gut–brain interface to environmental toxicants like pesticides [70]. Intervening in this axis through probiotic or prebiotic therapy may restore microbial balance and reduce neuroinflammatory consequences [71]. Clinical trials are beginning to explore gut-targeted therapies for managing mood disorders linked to environmental exposures [72]. Public health measures should include gut microbiota endpoints in pesticide risk assessments to capture these systemic effects [73]. Future research must focus on longitudinal human studies to validate the role of dysbiosis in pesticide-induced neurological diseases [74].This will provide a scientific foundation for therapeutic strategies that safeguard the microbiota–brain axis from environmental disrupt [75].

5. CONCLUSION

The gut microbiota, a diverse community of microorganisms in the digestive tract, plays a crucial role in digestion, immunity, and overall health. Disruption of this balance, known as dysbiosis, is linked to various diseases including IBD, metabolic, cardiovascular, and mental health disorders. Factors like diet, lifestyle, and environmental exposure influence microbiota composition, making its restoration a potential therapeutic target. The gut microbiota is a diverse community of microbes in the GI tract that aids in digestion, immunity, and maintaining bodily functions. It plays a vital role in the gut–brain axis, influencing mental health and contributing to disorders like anxiety, depression, IBS, and IBD when imbalanced. Key microbial species such as *Bacteroides* and *Bifidobacterium* are being studied for their impact on mood, inflammation, and metabolism. Gut dysbiosis refers to the imbalance of gut microbes caused by factors like antibiotics, poor diet, stress, and environmental exposures, leading to immune disruption, intestinal barrier damage, and various diseases. Pesticide exposure, especially chronic and dietary, alters gut microbiota composition and metabolites, contributing to metabolic, immune, and neurological disorders. Despite their agricultural importance, pesticides pose serious health risks—including hormone disruption, cancer, and neurotoxicity—highlighting the urgent need for safer alternatives. Pesticide-induced gut dysbiosis disrupts the gut–brain axis by compromising blood–brain barrier (BBB) integrity, reducing beneficial microbes, and altering neuroactive metabolite production. These changes trigger systemic inflammation, microglial activation, and impaired neurotransmission, contributing to neurodevelopmental and neurodegenerative disorders. Targeting the microbiota–brain axis through probiotics or gut-focused interventions offers promising therapeutic avenues for pesticide-linked neurological conditions.

REFERENCES

[1] Thursby E, Juge N. Introduction to the human gut microbiota. Biochem J. 2017; 474 (11): 1823–1836.

[2] Natividad JM, Verdu EF. Modulation of intestinal barrier by intestinal microbiota: Pathological and therapeutic implications. Pharmacological Research. 2013; 69(1): 42–51.

[3] Den Besten G, Van Eunen K, Groen AK, Venema K, Reijngoud DJ, Bakker BM. The role of short-chain fatty acids in the interplay between diet, gut microbiota, and host energy metabolism. Journal of lipid research. 2013; 54(9):2325-40.

[4] Bäumler AJ, Sperandio V. Interactions between the microbiota and pathogenic bacteria in the gut. Nature. 2016; 535(7610): 85-93.

[5] Gensollen T, Iyer SS, Kasper DL, Blumberg RS. How colonization by microbiota in early life shapes the immune system. Science. 2016; 352(6285):539-44.

[6] Facciotti F. Modulation of intestinal immune cell responses by eubiotic or dysbiotic microbiota in inflammatory bowel diseases. Pharmanutrition. 2022 ;21:100303.

[7] Afzaal M, Saeed F, Shah YA, Hussain M, Rabail R, Socol CT, Hassoun A, Pateiro M, Lorenzo JM, Rusu AV, Aadil RM. Human gut microbiota in health and disease: Unveiling the relationship. Frontiers in microbiology. 2022 ;13:999001

[8] AboNahas HH, Darwish AM, Abd EL-kareem HF, AboNahas YH, Mansour SA, Korra YH, Sayyed RZ, Abdel-Azeem AM, Saied EM. Trust your gut: the human gut microbiome in health and disease. Springer Nature. 2022: 53-96.

[9] Simoes CD, Maganinho M, Sousa AS. FODMAPs, inflammatory bowel disease and gut microbiota: updated overview on the current evidence. European journal of nutrition. 2022; 1:1-2.

[10] Clapp M, Aurora N, Herrera L, Bhatia M, Wilen E, Wakefield S. Gut microbiota's effect on mental health: The gut-brain axis. Clinics and practice. 2017 ;7(4):987.

[11] Afzaal M, Saeed F, Shah YA, Hussain M, Rabail R, Socol CT, Hassoun A, Pateiro M, Lorenzo JM, Rusu AV, Aadil RM. Human gut microbiota in health and disease: Unveiling the relationship. Frontiers in microbiology. 2022 ;13:999001.

[12] Falony G, Joossens M, Vieira-Silva S, Wang J, Darzi Y, Faust K, Kurilshikov A, Bonder MJ, Valles-Colomer M, Vandeputte D, Tito RY. Population-level analysis of gut microbiome variation. Science. 2016 ;352(6285):560-4.

[13] Heiss CN, Olofsson LE. The role of the gut microbiota in development, function and disorders of the central nervous system and the enteric nervous system. Journal of neuroendocrinology. 2019; 31(5):e12684.

[14] Singhal S, Bhadana R, Jain BP, Gautam A, Pandey S, Rani V. Role of gut microbiota in tumorigenesis and antitumoral therapies: an updated review. Biotechnology and Genetic Engineering Reviews. 2024; 40(4):3716-42.

[15] Sonnenburg JL, Backhed F. Diet–microbiota interactions as moderators of human metabolism. Nature. 2016; 535(7610):56-64.

[16] Jiang X, Zheng J, Zhang S, Wang B, Wu C, Guo X. Advances in the Involvement of Gut Microbiota in Pathophysiology of NAFLD. Frontiers in Medicine. 2020; 7:361.

[17] Winter SE, Bäumler AJ. Gut dysbiosis: Ecological causes and causative effects on human disease. Proceedings of the National Academy of Sciences. 2023; 120(50): 2316579120.

[18] Alagiakrishnan K, Morgadinho J, Halverson T. Approach to the diagnosis and management of dysbiosis. Frontiers in Nutrition. 2024; 11:1330903.

[19] Martinez JE, Kahana DD, Ghuman S, Wilson HP, Wilson J, Kim SC, Lagishetty V, Jacobs JP, Sinha-Hikim AP, Friedman TC. Unhealthy lifestyle and gut dysbiosis: a better understanding of the effects of poor diet and nicotine on the intestinal microbiome. Frontiers in endocrinology. 2021 ;12:667066.

[20] Zeng MY, Inohara N, Nuñez G. Mechanisms of inflammation-driven bacterial dysbiosis in the gut. Mucosal immunology. 2017; 10(1):18-26.

[21] Alagiakrishnan K, Morgadinho J, Halverson T. Approach to the diagnosis and management of dysbiosis. Frontiers in Nutrition. 2024; 11: 1330903.

[22] O'Riordan KJ, Moloney GM, Keane L, Clarke G, Cryan JF. The gut microbiota-immune-brain axis: Therapeutic implications. Cell Reports Medicine. 2025 ; 6(3): 101982.

[23] Ponziani FR, Zocco MA, D'Aversa F, Pompili M, Gasbarrini A. Eubiotic properties of rifaximin: Disruption of

the traditional concepts in gut microbiota modulation. World journal of gastroenterology. 2017; 23(25): 4491.

[24] Gibson GR, Roberfroid MB. Dietary modulation of the human colonic microbiota: introducing the concept of prebiotics. The Journal of nutrition. 1995 ;125(6): 1401-12.

[25] Hemarajata P, Versalovic J. Effects of probiotics on gut microbiota: mechanisms of intestinal immunomodulation and neuromodulation. Therapeutic advances in gastroenterology. 2013 ; 6(1): 39-51.

[26] Burcelin R. Gut microbiota and immune crosstalk in metabolic disease. Molecular metabolism. 2016; 5(9):771-81.

[27] Fung TC. The microbiota-immune axis as a central mediator of gut-brain communication. Neurobiology of disease. 2020 ; 136:104714.

[28] Matsuzaki R, Gunnigle E, Geissen V, Clarke G, Nagpal J, Cryan JF. Pesticide exposure and the microbiota-gut-brain axis. The ISME Journal. 2023 ;17(8):1153-66.

[29] Abou Diwan M, Lahimer M, Bach V, Gosselet F, Khorsi-Cauet H, Candela P. Impact of pesticide residues on the gut-microbiota–blood–brain barrier Axis: a narrative review. International Journal of Molecular Sciences. 2023 ;24(7):6147.

[30] Sharma T, Sirpu Natesh N, Pothuraju R, Batra SK, Rachagani S. Gut microbiota: a non-target victim of pesticide-induced toxicity. Gut Microbes. 2023;15(1):2187578.

[31] Damalas CA, Eleftherohorinos IG. Pesticide exposure, safety issues, and risk assessment indicators. International journal of environmental research and public health. 2011 ;8(5):1402-19.

[32] Tudi M, Daniel Ruan H, Wang L, Lyu J, Sadler R, Connell D, Chu C, Phung DT. Agriculture development, pesticide application and its impact on the environment. International journal of environmental research and public health. 2021 ;18(3):1112.

[33] Connell DW, Connell DW, Vowles PD, Warne MS, Hawker DW. Basic concepts of environmental chemistry. Boca Raton: CRC Press; 2005

[34] Imazaki I, Iizumi H, Ishikawa K, Sasahara M, Yasuda N, Koizumi S. Effects of thiophanate-methyl and azoxystrobin on the composition of Cercospora kikuchii populations with thiophanate-methyl-resistant strains. Journal of General Plant Pathology. 2006; 72: 292-300.

[35] Sharma T, Sirpu Natesh N, Pothuraju R, Batra SK, Rachagani S. Gut microbiota: a non-target victim of pesticide-induced toxicity. Gut Microbes. 2023 ;15(1):2187578.

[36] Motta EV, Raymann K, Moran NA. Glyphosate perturbs the gut microbiota of honey bees. Proceedings of the National Academy of Sciences. 2018 ;115(41):10305-10.

[37] Zhang J, Sun C, Jin X, Zhang Q. Gut dysbiosis and immune imbalance in pesticides exposure. Environ Toxicol Pharmacol. 2020;79:103443.

[38] Ramakrishna C, Mande SS. Environment shapes the microbiome in the gut. *Microb Ecol Health Dis.* 2019;30(1):1555077

[39] Zhang J, Sun C, Jin X, Zhang Q. Gut dysbiosis and immune imbalance in pesticides exposure. *Environ Toxicol Pharmacol.* 2020;79:103443.

[40] Mesnage R, Antoniou MN. Facts and fallacies in the debate on glyphosate toxicity. Frontiers in public health. 2017 ;5:298193.

[41] Zhu B, Wang X, Li L. Human gut microbiome: the second genome of human body. Protein & cell. 2010 ;1(8):718-25.

[42] Popli S, Badgujar PC, Agarwal T, Bhushan B, Mishra V. Persistent organic pollutants in foods, their interplay with gut microbiota and resultant toxicity. Science of The Total Environment. 2022 ;832:155084.

[43] Rieder R, Wisniewski PJ, Alderman BL, Campbell SC. Microbes and mental health: A review. Brain, behavior, and immunity. 2017 ;66:9-17.

[44] Velmurugan G, Ramprasath T, Gilles M, Swaminathan K, Ramasamy S. Gut microbiota, endocrine-disrupting chemicals, and the diabetes epidemic. *Trends Endocrinol Metab*. 2017;28(8):612–625.

[45] Braniste V, Al-Asmakh M, Kowal C, Anuar F, Abbaspour A, Tóth M, Korecka A, Bakocevic N, Ng LG, Kundu P, Gulyás B. The gut microbiota influences blood-brain barrier permeability in mice. Science translational medicine. 2014 ;6(263): 263ra158-.

[46] Petrov VA, Saltykova IV, Zhukova IA, Alifirova VM, Zhukova NG, Dorofeeva YB, Tyakht AV, Kovarsky BA, Alekseev DG, Kostryukova ES, Mironova YS. Analysis of gut microbiota in patients with Parkinson's disease. Bulletin of experimental biology and medicine. 2017 ;162:734-7.

[47] Silva YP, Bernardi A, Frozza RL. The role of short-chain fatty acids from gut microbiota in gut-brain communication. Frontiers in endocrinology. 2020 ;11:508738.

[48] Jiang C, Li G, Huang P, Liu Z, Zhao B. The gut microbiota and Alzheimer's disease. Journal of Alzheimer's Disease. 2017 ;58(1):1-5.

[49] Fung TC, Olson CA, Hsiao EY. Interactions between the microbiota, immune and nervous systems in health and disease. Nature neuroscience. 2017 ;20(2):145-55.

[50] Gao K, Mu CL, Farzi A, Zhu WY. Tryptophan metabolism: a link between the gut microbiota and brain. Advances in nutrition. 2020 ;11(3):709-23.

[51] Cryan JF, O'Riordan KJ, Cowan CS, Sandhu KV, Bastiaanssen TF, Boehme M, Codagnone MG, Cussotto S, Fulling C, Golubeva AV, Guzzetta KE. The microbiota-gut-brain axis. Physiological reviews. 2019 ;99(4):1877-2013.

[52] Tamtaji OR, Heidari-Soureshjani R, Mirhosseini N, Asemi Z. Probiotic and prebiotic supplementation for the management of multiple sclerosis: A systematic review. Current Pharmaceutical Design,(2019); 25(4): 437–445.

[53] Cryan JF, Dinan TG. Mind-altering microorganisms: the impact of the gut microbiota on brain and behaviour. Nature reviews neuroscience. 2012 ;13(10):701-12.

[54] Strandwitz P. Neurotransmitter modulation by the gut microbiota. *Brain Res*. 2018;1693, 128–133.

[55] Fang B, Li JW, Zhang M, Ren FZ, Pang GF. Chronic chlorpyrifos exposure elicits diet-specific effects on metabolism and the gut microbiome in rats. Food and Chemical Toxicology. 2018 ;111:144-52.

[56] Prouty C, Mohebbi S, Zhang Q. Extreme weather events and wastewater infrastructure: A system dynamics model of a multi-level, socio-technical transition. Science of the Total Environment. 2020 ;714:136685.

[57] Li C, Zhang W, Jiang Y, Gong X. Effects of chlorpyrifos on gut microbiota and metabolite in mice. *Sci Total Environ*. 2020;714:136685.

[58] Rogers GB, Keating DJ, Young RL, Wong ML, Licinio J, Wesselingh S. From gut dysbiosis to altered brain function and mental illness: mechanisms and pathways. Molecular psychiatry. 2016 ;21(6):738-48.

[59] Fung TC, Olson CA, Hsiao EY. Interactions between the microbiota, immune and nervous systems in health and disease. Nature neuroscience. 2017 ;20(2):145-55..

[60] Braniste V, Al-Asmakh M, Kowal C, Anuar F, Abbaspour A, Tóth M, Korecka A, Bakocevic N, Ng LG, Kundu P, Gulyás B. The gut microbiota influences blood-brain barrier permeability in mice. Science translational medicine. 2014 ;6(263):263ra158-.

[61] Singh S, Sharma P, Pal N, Kumawat M, Shubham S, Sarma DK, Tiwari RR, Kumar M, Nagpal R. Impact of environmental pollutants on gut microbiome and mental health via the gut–brain axis. Microorganisms. 2022 ;10(7):1457.

[62] Bonaz B, Bazin T, Pellissier S. The vagus nerve at the interface of the microbiota-gut-brain axis. Frontiers in neuroscience. 2018;12:336468.

[63] Rueda-Ruzafa L, Cruz F, Roman P, Cardona D. Gut microbiota and neurological effects of glyphosate. Neurotoxicology. 2019 ;75:1-8.

[64] Zheng R, Romero-del Rey R, Ruiz-Moreno F, Garcia-Gonzalez J, Requena-Mullor M, Navarro-Mena AÁ, López-Villén A, Alarcon-Rodriguez R. Depressive symptoms and suicide attempts among farmers exposed to pesticides. Environmental toxicology and pharmacology. 2024 ;108:104461.

[65] Asadi A, Shadab Mehr N, Mohamadi MH, Shokri F, Heidary M, Sadeghifard N, Khoshnood S. Obesity and gut–microbiota–brain axis: A narrative review. Journal of clinical laboratory analysis. 2022 May;36(5):e24420.

[66] Yang Y, Zhou S, Xing Y, Yang G, You M. Impact of pesticides exposure during neurodevelopmental period on autism spectrum disorders–A focus on gut microbiota. Ecotoxicology and environmental safety. 2023 ;260:115079..

[67] Bellot M, Carrillo MP, Bedrossiantz J, Zheng J, Mandal R, Wishart DS, Gómez-Canela C, Vila-Costa M, Prats E, Piña B, Raldúa D. From dysbiosis to neuropathologies: Toxic effects of glyphosate in zebrafish. Ecotoxicology and environmental safety. 2024 ;270:115888.

[68] Cryan JF, O'Riordan KJ, Cowan CS, Sandhu KV, Bastiaanssen TF, Boehme M, Codagnone MG, Cussotto S, Fulling C, Golubeva AV, Guzzetta KE. The microbiota-gut-brain axis. Physiological reviews. 2019

[69] Mesnage R, Renney G, Séralini GE, Ward M, Antoniou MN. Multiomics reveal non-alcoholic fatty liver disease in rats following chronic exposure to an ultra-low dose of Roundup herbicide. Scientific reports. 2017

;7(1):39328.

[70] Tsiaoussis J, Antoniou MN, Koliarakis I, Mesnage R, Vardavas CI, Izotov BN, Psaroulaki A, Tsatsakis A. Effects of single and combined toxic exposures on the gut microbiome: Current knowledge and future directions. Toxicology letters. 2019 ;312:72-97.

[71] Farkhondeh T, Mehrpour O, Forouzanfar F, Roshanravan B, Samarghandian S. Oxidative stress and mitochondrial dysfunction in organophosphate pesticide-induced neurotoxicity and its amelioration: a review. Environmental Science and Pollution Research. 2020 ;27:24799-814.

[72] Tang Q, Jin G, Wang G, Liu T, Liu X. Pesticide exposure and risk of depression: a meta-analysis of observational studies. *Int J Environ Res Public Health*. 2020;17(16):5794

[73] Mesnage R, Antoniou MN. Computational modelling provides insight into the effects of glyphosate on the shikimate pathway in the human gut microbiome. Current research in toxicology. 2020 ;1:25-33.

[74] Clarke G, Grenham S, Scully P, Fitzgerald P, Moloney RD, Shanahan F, Dinan TG, Cryan J. The microbiome-gut-brain axis during early life regulates the hippocampal serotonergic system in a sex-dependent manner. Molecular psychiatry. 2013 ;18(6):666-73.

[75] Nicholson JK, Holmes E, Kinross J, Burcelin R, Gibson G, Jia W, Pettersson S. Host-gut microbiota metabolic interactions. Science. 2012 ;336(6086):1262-7.