(RESEARCH ARTICLE)

Altered functional connectivity in fronto-limbic circuits, dysregulation of the hypothalamic–pituitary–adrenal axis (HPA), and serotonergic dysfunction in Major Depressive Disorder (MDD)

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Abstract

Major Depressive Disorder (MDD) is a complex neuropsychiatric condition characterized by widespread alterations in neural circuitry, neurotransmission, and neuroendocrine regulation. This review integrates findings from neuroimaging, molecular, and pharmacological studies to elucidate the neurobiological substrates of MDD, with particular emphasis on fronto-limbic network dysfunction, hypothalamic–pituitary–adrenal (HPA) axis dysregulation, and serotonergic signaling abnormalities. Convergent evidence from resting-state and task-based functional MRI indicates reduced functional connectivity within prefrontal–limbic circuits, including the medial prefrontal cortex, anterior cingulate cortex, amygdala, hippocampus, and hypothalamus, alongside impaired top-down regulation of emotional processing. At the neurochemical level, MDD is associated with serotonergic hypoactivity, altered receptor dynamics (notably 5-HT1A and 5-HT2A), and disrupted monoamine transport, as well as emerging dysregulation in glutamatergic and GABAergic systems that contribute to excitatory–inhibitory imbalance. Additionally, reduced expression of brain-derived neurotrophic factor (BDNF) and impaired synaptic plasticity are consistently observed, linking molecular deficits to circuit-level dysfunction. Hyperactivation of the HPA axis and chronic hypercortisolemia further exacerbate hippocampal and prefrontal abnormalities, reinforcing maladaptive stress responses. Collectively, these findings support a systems-level model in which MDD arises from the interaction of dysfunctional neural networks, impaired neuroplasticity, and neuroendocrine imbalance. Advancing this integrative framework is critical for the development of targeted, mechanism-based therapeutic interventions.

1. Introduction

Human mental health is influenced by multiple factors, including personal desires, satisfaction levels, self-worth, and genetic predisposition. Psychology, defined as the scientific study of behavior and mental processes, examines how internal states and external environments affect individuals [1]. Traditional models have emphasized monoaminergic dysfunction, particularly involving serotonin; however, emerging evidence indicates that depression arises from complex interactions among neurotransmitter systems, neuroplasticity deficits, and neuroendocrine dysregulation. This review synthesizes current knowledge on the neurobiology of depression, focusing on neural circuitry, neurotransmitter imbalance, and molecular mechanisms such as brain-derived neurotrophic factor (BDNF) signaling and glutamatergic dysfunction. Recent advances highlight the role of impaired synaptic plasticity, altered functional connectivity in fronto-limbic circuits, and dysregulation of the hypothalamic–pituitary–adrenal (HPA) axis. In

particular, reduced BDNF expression and glutamatergic abnormalities have been implicated in the pathophysiology of depression and in the rapid antidepressant effects of novel treatments such as ketamine. Epidemiological data indicate that depression affects approximately 3.8% of the global population and is strongly associated with increased suicide risk. Possibly due to the persistent influence of a positivistic attitude, paired with a scientistic framework mixed with dubious postmodernist considerations, human life is considered as characterized by intelligence, reasoning, and self-awareness, often in strong opposition to rapid technological advancement and materialistic lifestyles, which have significantly altered human behavior and health. While modernization and technological developments have improved convenience and access to information -albeit not necessarily scientifically solid information-, it has also contributed to a rise in both physical and mental health challenges.

2. Method

This study employed a narrative literature review approach to synthesize current evidence on the neurobiological mechanisms underlying Major Depressive Disorder (MDD), with a specific focus on fronto-limbic functional connectivity, hypothalamic–pituitary–adrenal (HPA) axis dysregulation, and serotonergic dysfunction. A comprehensive search of electronic databases, including PubMed, NIH, Scopus, ReserchGate, Web of Science, and Academia.edu was conducted to identify relevant peer-reviewed articles published between 2000 and 2026. Search terms were combined using Boolean operators and included: "Major Depressive Disorder," "MDD," "functional connectivity," "fronto-limbic circuits," "prefrontal cortex," "amygdala," "hippocampus," "hypothalamus," "HPA axis," "cortisol," "serotonin," "5-HT1A," "5-HT2A," "BDNF," "neuroplasticity," "glutamate," and "GABA." Additional studies were identified through backward and forward citation tracking of key articles. Inclusion criteria comprised (1) original research studies, meta-analyses, and systematic reviews; (2) human studies involving individuals diagnosed with MDD based on standardized criteria (e.g., DSM-IV or DSM-5); (3) studies employing neuroimaging techniques (e.g., resting-state or task-based functional MRI), molecular or biochemical assays, or pharmacological investigations; and (4) articles published in English. Exclusion criteria included case reports, non-peer-reviewed sources, studies focusing exclusively on other psychiatric disorders without clear relevance to MDD, and animal-only studies unless directly informing translational mechanisms. Data extraction focused on key domains, including alterations in brain network connectivity, neurotransmitter system dysfunction, neuroendocrine markers (particularly cortisol and HPA axis activity), and molecular indicators of neuroplasticity such as BDNF expression. Findings were organized thematically into three primary domains: (1) fronto-limbic circuit dysfunction, (2) serotonergic and broader neurotransmitter system alterations, and (3) HPA axis dysregulation and stress-related mechanisms. Given the heterogeneity of methodologies across studies, a quantitative meta-analysis was not performed. Instead, results were qualitatively synthesized to identify convergent patterns, inconsistencies, and emerging trends. Emphasis was placed on integrating findings across levels of analysis—from molecular and cellular mechanisms to large-scale brain network dynamics—to develop a comprehensive, systems-level understanding of MDD.

3. Depression and its Biological Basis

Among these disorders, depression is a major mood disorder characterized by persistent sadness, loss of interest, and emotional instability. It can range from mild symptoms to severe conditions such as major depressive disorder (MDD). Historically, the causes of mental illness were attributed to supernatural or environmental factors; however, modern research emphasizes biological explanations, including genetic, neurological, and biochemical components. More specifically, depression is associated with altered activity in fronto-limbic circuits, including the prefrontal cortex, amygdala, hippocampus, and hypothalamus. These regions regulate emotional processing, stress response, and cognitive control. Disruptions in connectivity within these circuits contribute to mood dysregulation and impaired emotional processing. Recent neuroimaging and computational studies demonstrate that depression involves network-level dysfunction, rather than isolated regional abnormalities, supporting a systems neuroscience perspective. From a broad-scale analysis, the central nervous system plays a vital role in emotional regulation, involving brain structures such as the amygdala, hippocampus, prefrontal cortex, and hypothalamus, and specific systems as follows:

- Monoaminergic System: Traditional antidepressants target monoamines such as serotonin, dopamine, and norepinephrine. These neurotransmitters regulate mood, motivation, and cognition. However, evidence suggests that monoamine dysfunction alone cannot fully explain depression.
- Glutamatergic System: Emerging evidence indicates that glutamate, the primary excitatory neurotransmitter, plays a central role in depression. Dysregulation of glutamatergic signaling and NMDA receptor function has been linked to depressive pathology [2][3]. Rapid-acting antidepressants such as ketamine target this system, producing fast clinical effects.

- GABAergic System: Reduced inhibitory GABA signaling has also been observed in individuals with depression, contributing to excitatory–inhibitory imbalance and neural circuit dysfunction.
- Neurotransmitters—chemical messengers that transmit signals between neurons—are essential for regulating mood and cognition [1]. Key neurotransmitters include serotonin, dopamine, norepinephrine, gamma-aminobutyric acid (GABA), and glutamate.
- Serotonin, also known as 5-hydroxytryptamine, is particularly associated with depression. It regulates mood, sleep, appetite, and cognitive functions. Approximately 90% of serotonin is produced in the gastrointestinal tract, while the remaining 10% is synthesized in the brain [2]. Low levels of serotonin are linked to depression and anxiety. Additionally, hormonal imbalances, such as elevated glucocorticoids during stress and thyroid hormone deficiencies (hypothyroidism), can contribute to depressive symptoms.

Furthermore, Neuroplasticity deficits are a key feature of depression. Brain-derived neurotrophic factor (BDNF) is essential for neuronal survival, synaptic plasticity, and neurogenesis. Reduced BDNF expression has been consistently observed in the hippocampus and prefrontal cortex of depressed individuals [4][5]. Antidepressant treatments—including pharmacological and non-pharmacological interventions—have been shown to enhance BDNF signaling and promote synaptic remodeling. With regard to brain areas and their relative functional activity, fronto-limbic circuits, encompassing the prefrontal cortex (PFC), anterior cingulate cortex (ACC), amygdala, hippocampus, and hypothalamus, are pivotal for emotion regulation and cognitive control in MDD.
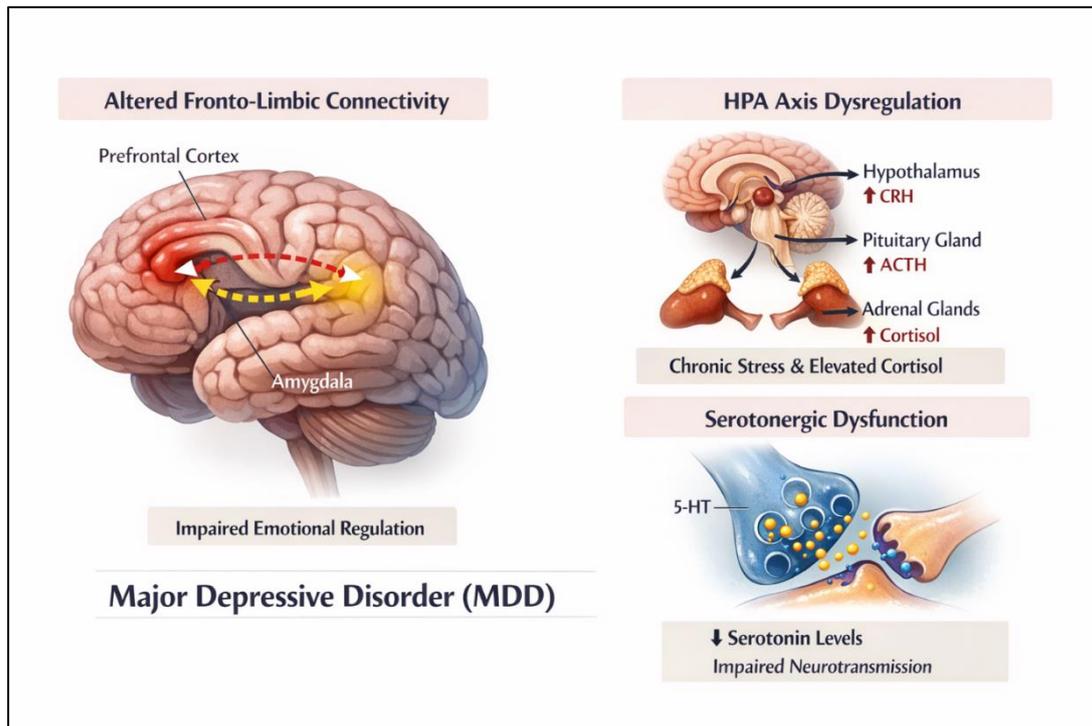

Figure 1 Graphic representation of overall impaired emotional regulation, with analysis of altered functional connectivity in fronto-limbic circuits, HPA axis dysregulation, and serotonergic dysfunction in Major Depressive Disorder (MDD)

Resting-state functional MRI (rs-fMRI) studies consistently demonstrate hypo-connectivity within these networks, reflecting disrupted integration that perpetuates negative affect bias [13,14]. In a cohort of 55 MDD patients and 40 controls, voxel-based analysis revealed significantly decreased rs-fMRI connectivity between the bilateral hypothalamus and right insula, superior temporal gyrus, inferior frontal gyrus, and Rolandic operculum. This hypothalamic decoupling suggests impaired visceral and emotional signaling, contributing to MDD persistence, as indicated in Fig. 2. Similarly, task-based fMRI during negative emotional processing in 34 unmedicated female MDD patients showed reduced effective connectivity from the orbitofrontal cortex (OFC) to the parahippocampal gyrus (PHG), alongside absent modulation from primary visual cortex (V1) to OFC, contrasting with healthy controls [13, 14]. These findings indicate deficient inhibitory control over limbic responses, fostering sustained sadness. Broader network analyses highlight global FC reductions in medial PFC and subgenual ACC, with effect sizes up to Hedges' g = -1.48 . In 82 participants, MDD patients exhibited lower whole-brain coherence in ventromedial PFC, correlating with

Montgomery-Åsberg Depression Rating Scale (MADRS) scores (r = -0.47). Dynamic FC approaches further reveal increased static FC but decreased variability within the default mode network (DMN), particularly between DMN and frontoparietal nodes, in 27 MDD patients versus controls [14]. This temporal rigidity may underlie ruminative thinking. Striatal involvement extends fronto-limbic alterations; in 50 unmedicated MDD patients, reduced FC between dorsal putamen subregions and postcentral gyrus/precuneus was observed, independent of HAMD-24 scores . Multimodal studies confirm spatial selectivity in limbic/DMN hubs, with reduced cerebral blood flow (CBF) preceding FC impairments [13, 14]. In 35 MDD patients, anterior/middle/superior frontal gyri and right PHG showed decreased degree centrality, recovering post-treatment [14, 15]. Whole-brain parcellation in 20 MDD patients identified hypo-connectivity in frontal-limbic, parietal-occipital, and occipital regions, beyond canonical emotion networks . These patterns suggest widespread sensorimotor integration deficits [15].

Table 1 Persistence of Major Depressive Disorder (MDD) in activated brain region (brain pairs) and relative neurological method

Region Pair	MDD vs. Controls (FC Change)	Method	Key Reference
Hypothalamus - Right Insula	Decreased (p<0.05)	rs-fMRI, voxel-based	(Wang et al., 2019)
OFC - PHG	Reduced inhibitory modulation	Task fMRI, DCM	(Tak et al., 2021)
Medial PFC - Whole Brain	Global reduction (g=-1.48)	rs-fMRI, global connectivity	(Murrough et al., 2016)
DMN - Frontoparietal	Decreased variability	Dynamic FC	(Demirtaş et al., 2016)
Dorsal Putamen - Precuneus	Decreased (p<0.008, TFCE)	rs-fMRI, seed-based	(Chen et al., 2019)
Frontal Gyrus - PHG	Decreased centrality	Multimodal fMRI	(Sheng et al., 2018)

In regard to Serotonin dysfunction [Fig. 3], it is important to note that this neurotransmitter odulates mood, cognition, and stress via transporters (SERT), autoreceptors (5-HT1A), and postsynaptic receptors (5-HT2A/1A/7). MDD features presynaptic hypoactivity, increased 5-HT2A sensitivity, decreased 5-HT1A function, and altered uptake [16]. Moreover, platelet studies in 30 MDD patients revealed lower Vmax for [14C]5-HT uptake at baseline versus controls, with first-episode patients showing reduced [3H]paroxetine Bmax . Post-sertraline/paroxetine (6 months), Vmax decreased further, Km increased, correlating with plasma levels in first-episode cases [18]. This suggests adaptive transporter downregulation, though recurrent MDD resists changes [18, 19] As far as receptor dynamics are concerned, which is an essential aspect of the neurodynamic examination at hand, HPA hypercortisolemia desensitizes 5-HT1A, impairing autoinhibition and LHPA regulation [17]. In suicide-prone MDD, absent HPT-dopamine links and reduced 5-HT transmission exacerbate HPA hyperactivity[17, 18]. Vortioxetine and vilazodone target 5-HT1A agonism and 5-HT3/7 antagonism, improving cognition/anxiety beyond SSRIs [18, 19]. Finally from an extended mind-body connection perspective, gut microbiota influences 5-HT-HPA via cytokines, with MDD showing reduced central 5-HT [17, 18]. Antidepressants enhance 5-HT transmission, dampening catecholamines, but low remission rates highlight multimodal needs [19, 20].

Table 2 Major Depressive Disorder (MDD) with specific brain regions and circuitry and relative empirical laboratory observations

Region/Circuit	MDD Alteration	Evidence Summary
Medial PFC	Reduced global connectivity	Decreased FC with limbic areas; linked to rumination
Amygdala-PFC	Hyperconnectivity/ineffective regulation	Exaggerated threat response; fronto-limbic imbalance
Hypothalamus	HPA hyperactivity	↑CRH drives cortisol excess; early stress predictor
Raphe Nuclei	Serotonergic hypoactivity	↓5-HT transmission modulates HPA/limbic dysfunction
Hippocampus	Volume reduction, poor feedback	Glucocorticoid neurotoxicity from chronic HPA

4. Etiological causes and Prevalence

Depression is one of the most common mental health disorders worldwide, affecting approximately 3.8% of the global population, including 5% of adults and 5.7% of older adults [3]. It is more prevalent in women than men and poses a significant risk for suicide. Globally, over 700,000 people die by suicide each year, making it a leading cause of death among young individuals aged 15–29 [3]. Depression affects individuals regardless of age, gender, or socioeconomic status. Research suggests that vulnerability to depression is influenced by a combination of biological predisposition and environmental stressors, often explained by the stress-vulnerability model [1]. Depression arises from a complex interaction of multiple factors, including:

4.1. Genetic predisposition

- Childhood trauma, abuse, or neglect
- Loss of significant relationships
- Negative cognitive patterns
- Chronic illness
- Substance abuse
- Loneliness and stressful life events

Environmental factors, such as reduced sunlight exposure, can also lead to seasonal affective disorder (SAD), a type of depression that occurs during specific times of the year, typically in winter [4]. Furthermore, since MDD is associated with altered activity in fronto-limbic circuits, including the prefrontal cortex, amygdala, hippocampus, and hypothalamus, it is important to understand, also from a clinical standpoint, how these regions regulate emotional processing, stress response, and cognitive control. Disruptions in connectivity within these circuits contribute to mood dysregulation and impaired emotional processing [10]. More in detail, recent neuroimaging and computational studies demonstrate that depression involves network-level dysfunction, rather than isolated regional abnormalities, supporting a systems neuroscience perspective [6, 11].

5. Diagnostic considerations

Diagnosing depression involves a comprehensive evaluation of both physical and psychological health. Primary care physicians often conduct initial assessments, including medical history, physical examinations, and laboratory tests such as complete blood count and thyroid function tests. Thyroid imbalances can significantly affect mood and cognition. Following initial assessment, patients may be referred to a psychiatrist for further evaluation using standardized diagnostic criteria such as the DSM-5. Symptoms considered include persistent sadness, loss of interest, fatigue, cognitive impairment, and suicidal ideation [5]. Common diagnostic symptoms of depression include:

- Persistent sadness, emptiness, or hopelessness
- Loss of interest in previously enjoyed activities
- Changes in appetite and weight
- Insomnia or sleep disturbances
- Fatigue and low energy
- Difficulty concentrating or making decisions
- Feelings of guilt or worthlessness
- Suicidal thoughts or behaviors

Depression is a treatable condition, and effective management often involves a combination of medical and psychological interventions. Pharmacological Treatments used include:

- Antidepressants (e.g., SSRIs such as fluoxetine, sertraline)
- Tricyclic antidepressants and MAO inhibitors
- Antipsychotics for severe cases
- Anxiolytics for short-term anxiety relief
- Lithium carbonate for mood stabilization in bipolar disorder

Moreover, psychotherapy is a key component of treatment. Common approaches include:

- Cognitive Behavioral Therapy (CBT)

- Dialectical Behavior Therapy (DBT)
- Psychoanalytic therapy
- Humanistic therapy
- Family and group therapy

CBT is particularly effective in helping individuals identify and modify negative thought patterns, while other treatments include

- Electroconvulsive Therapy (ECT): Used in severe or treatment-resistant depression
- Hospitalization: Necessary in high-risk cases
- Neurosurgical procedures: Rarely used (e.g., cingulotomy)

In addition to professional treatment, lifestyle changes play an essential role in managing depression:

- Regular physical exercise
- Adequate sleep
- Healthy diet
- Avoidance of alcohol and drugs
- Social engagement and positive environments
- Mindfulness and relaxation techniques

Complementary therapies such as meditation, music therapy, and art therapy may also provide benefits.

6. Conclusion

Depression is a serious and widespread mental health disorder influenced by biological, psychological, and environmental factors. While traditional monoaminergic models remain relevant, emerging evidence highlights the importance of glutamatergic signaling and BDNF-mediated plasticity. The evidence reviewed here demonstrates that alterations in fronto-limbic functional connectivity—particularly involving the medial prefrontal cortex, anterior cingulate cortex, amygdala, hippocampus, and hypothalamus—disrupt the balance between cognitive control and emotional processing, thereby promoting persistent negative affect and maladaptive rumination. These circuit-level abnormalities are closely linked to impaired top-down regulatory mechanisms and reduced network flexibility.

At the molecular and neurochemical level, serotonergic dysfunction, including altered receptor sensitivity (e.g., 5-HT1A and 5-HT2A) and transporter dynamics, contributes to dysregulated mood and stress responsivity. Importantly, these monoaminergic disturbances do not occur in isolation but interact with broader excitatory–inhibitory imbalances involving glutamatergic and GABAergic systems. Concurrently, reduced expression of brain-derived neurotrophic factor (BDNF) and impaired synaptic plasticity provide a mechanistic bridge between cellular-level deficits and large-scale network dysfunction. Dysregulation of the hypothalamic–pituitary–adrenal (HPA) axis further amplifies these pathological processes. Chronically elevated glucocorticoid levels exert neurotoxic effects on the hippocampus and prefrontal cortex, weaken negative feedback regulation, and reinforce maladaptive stress responses. The bidirectional interactions among HPA axis hyperactivity, serotonergic signaling, and fronto-limbic circuitry underscore the integrated nature of MDD pathophysiology. Taken together, these findings support a unified, multidimensional model in which MDD emerges from the convergence of disrupted neural connectivity, impaired neuroplasticity, and persistent neuroendocrine imbalance. This integrative framework has important clinical implications, emphasizing the need for multimodal, mechanism-based interventions that extend beyond traditional monoaminergic approaches. Future research should prioritize longitudinal and multimodal studies to clarify causal relationships among these systems and to identify reliable biomarkers for diagnosis, prognosis, and treatment response. Advancing such precision-based strategies will be critical for improving therapeutic outcomes and reducing the global burden of depression. While advances in neuroscientific research are paving the way for more effective and targeted treatments, early diagnosis and appropriate treatment are essential for recovery and improved well-being.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Statement of informed consent

Informed consent was obtained from all individual participants included in the studies analyzed. All protocols in this study were approved by the VAAS Committee

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References

[1] Wade C, Tavris C. Invitation to Psychology. 5th ed. New York: Pearson; 2012.

[2] Cleveland Clinic. Serotonin: What is it, function & levels [Internet]. 2025 May 7 [cited 2026 Mar 17]. Available from: https://my.clevelandclinic.org/health/articles/22572-serotonin

[3] World Health Organization. Depression [Internet]. [cited 2026 Mar 17]. Available from: https://www.who.int/news-room/fact-sheets/detail/depression;

[4] Correia AS, Cardoso A, Vale N. BDNF in major depressive disorder. Pharmaceutics. 2023;15:2081; Cleveland Clinic. Seasonal affective disorder (seasonal depression) [Internet]. 2025 Jul 14 [cited 2026 Mar 17]. Available from: https://my.clevelandclinic.org/health/diseases/9293-seasonal-depression

[5] Pardossi S, Fagiolini A, Cuomo A. Variations in BDNF and their role in antidepressant mechanisms. Int J Mol Sci. 2024;25:13098; Mayo Foundation for Medical Education and Research. Depression (major depressive disorder): Diagnosis and treatment [Internet]. 2022 Oct 14 [cited 2026 Mar 17]. Available from: https://www.mayoclinic.org/diseases-conditions/depression/diagnosis-treatment/dr-c20356013

[6] Queensland Brain Institute. What are neurotransmitters? [Internet]. 2022 Jul 29 [cited 2026 Mar 17]. Available from: https://qbi.uq.edu.au/brain/brain-functions/what-are-neurotransmitters

[7] American Psychiatric Association. What is depression? [Internet]. [cited 2026 Mar 17]. Available from: https://www.psychiatry.org/patients-families/depression/what-is-depression

[8] World Health Organization. Depression [Internet]. Available from: https://www.who.int/news-room/fact-sheets/detail/depression

[9] McIntyre RS, Jain R. Glutamatergic modulators for major depression from theory to clinical use. CNS Drugs. 2024;38:869–890.

[10] Tomasi, D., Lateral frontoparietal network (L-FPN)and Midcingulo-insular network (M-CIN) Activation in Truth vs. Delusion discrimination processes within Psychopathology. Sofia, BG: Sofia Philosophical Review 12(25) - SPhR 20th Anniversary Special Issue, 2026

[11] Wei X. The glutamatergic system in the development of stress-induced depression. Ann Med Surg. 2024;86:5930–5937.

[12] Jha MK, et al. Neuroplasticity and mechanisms of antidepressants. Biomedicines. 2024;12:2744.

[13] Murrough, J., Abdallah, C., Anticevic, A., Collins, K., Geha, P., Averill, L., Schwartz, J., Dewilde, K., Averill, C., Yang, G. J.-W., Wong, E., Tang, C. Y., Krystal, J., Iosifescu, D., & Charney, D. (2016). Reduced global functional connectivity of the medial prefrontal cortex in major depressive disorder. Human Brain Mapping, 37 https://doi.org/10.1002/hbm.23235

[14] Demirtaş, M., Tornador, C., Falcón, C., López-Solà, M., Hernández-Ribas, R., Pujol, J., Menchón, J., Ritter, P., Cardoner, N., Soriano-Mas, C., & Deco, G. (2016). Dynamic functional connectivity reveals altered variability in functional connectivity among patients with major depressive disorder. Human Brain Mapping, 39. 2918–2930. https://doi.org/10.1002/hbm.23215

[15] Wang, D., Xue, S., Tan, Z., Wang, Y., Lian, Z., & Sun, Y. (2019). Altered hypothalamic functional connectivity patterns in major depressive disorder Neuroreport, https://doi.org/10.1097/WNR.0000000000001335

[16] Cubała, W., & Landowski, J. (2006). [Serotoninergic system and limbic-hypothalamic-pituitary-adrenal axis (LHPA axis) in depression]. Psychiatria Polska, 403, 415–30.

[17] Stain-Malmgren, R., Ae, K., Åberg-Wistedt, A., & Tham, A. (2001). Serotonergic function in major depression and effect of sertraline and paroxetine treatment. International Clinical Psychopharmacology, 16. 93–101. https://doi.org/10.1097/00004850-200103000-00004

[18] Blier, P., & Mansari, M. E. (2013). Serotonin and beyond: therapeutics for major depression. Philosophical Transactions of the Royal Society B: Biological Sciences, 368. https://doi.org/10.1098/rstb.2012.0536

[19] Okada M, Matsumoto R, Yamamoto Y, Fukuyama K. Effects of subchronic administrations of vortioxetine on thalamocortical glutamatergic transmission associated with serotonin 5-HT7 receptor. Int J Mol Sci. 2021;22(3):1351.

[20] Webb S, Tomasi D. Human gastrointestinal microbiota and neural activity: effects of probiotics on mental and GI health. J Med Res Health Sci. 2020;3(9):1070-1076. doi:10.15520/jmrhs.v3i9.244