

REVIEW ARTICLE

Nanotherapeutics and Psychopathology: Revolutionizing Mental Health Diagnosis and Treatment with Bioengineered Nanoplatforms

Abdul Amir H. Kadhum¹, Hoda Safa², Rosa Davallou³, Zahra Geramizadeh^{4,5}, Atabak Naiyeri⁶, Zeynab Tajeryan⁷, Leila Kosari Esfahani^{8*}

¹ College of Medicine, University of Al-Ameed, Karbala, Iraq.

² Department of Gastroenterology, Hormozgan University of Medical Sciences, Bandar Abbas, Iran.

³ Department of Neurology, Sayyad Shirazi Hospital, Golestan University of medical Sciences, Gorgan, Iran.

⁴ Faculty of Cognitive Science, University of Tehran, Tehran, Iran.

⁵ Grand Canyon University, Phoenix, AZ, USA.

⁶ Department of Animal Biology, Faculty of Natural Sciences, University of Tabriz, Tabriz, Iran.

⁷ Department of Community Health and Health Behavior, State University of New York, SUNY, at Buffalo, USA.

⁸ Department of Psychology, Birjand Branch, Islamic Azad University, Birjand, Iran.

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ABSTRACT

This review evaluates how nanotherapeutics can improve the diagnosis and treatment of psychopathology by addressing limitations of conventional pharmacotherapy, such as poor blood–brain (BBB) barrier penetration and off-target effects in disorders like depression and schizophrenia. It summarizes key classes of nanoplatforms lipid-based, polymeric, inorganic, and hybrid systems and their use in targeted brain delivery, controlled drug release, and modulation of pathways including neurotransmission, neuroinflammation, and neuroplasticity, with a particular focus on theranostic systems that combine imaging and therapy. The article also highlights nanoparticle-enabled biosensors and imaging agents for sensitive detection of neuropsychiatric biomarkers, alongside nanoformulations of psychotropic drugs, gene-based strategies, and neuromodulatory platforms that show promise in preclinical and early translational studies. Finally, it discusses major translational challenges safety, scalability, regulation, and ethical considerations and outlines future directions toward AI-assisted, personalized nanomedicine for mental health care.

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INTRODUCTION

Psychopathology encompasses a broad spectrum of mental health disorders, including schizophrenia, depression, and anxiety, that collectively impose a profound burden on individuals, healthcare systems, and societies worldwide. According to the World Health Organization (WHO), depressive disorders alone affect more than 264 million people globally, contributing significantly to disability and reduced quality of life [1]. Despite the availability of

pharmacotherapies, current treatments are often limited by suboptimal brain penetration due to the restrictive nature of the blood–brain barrier (BBB), delayed onset of action, incomplete symptom control, and frequent adverse effects, all of which underscore the urgent need for more precise and effective therapeutic strategies [1-4].

Nanotherapeutics have emerged as a promising class of bioengineered platforms designed to address many of these limitations by enabling targeted and controlled delivery of drugs to

* Corresponding Author Email: Leila.kosari.70.psy@gmail.com



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the central nervous system (CNS). Advanced nanocarriers such as liposomes, polymeric nanoparticles, dendrimers, and other nanoscale delivery systems can encapsulate therapeutic agents, enhancing their stability, improving pharmacokinetics, and facilitating passage across the BBB [5, 6]. By enabling site-specific delivery, modulating release profiles, and reducing off-target toxicity, these nanosystems hold particular promise for overcoming drug resistance mechanisms and enhancing the safety and efficacy of treatments for CNS disorders [2, 7].

Within this evolving landscape, the review aims to provide a comprehensive and critical analysis of current advances in nano-enabled approaches for mental health disorders. The focus is on theranostic nanoplatfroms that integrate diagnostic and therapeutic functions, enabling simultaneous disease detection, monitoring, and intervention to support personalized and precision psychiatry [8,9]. The novelty of this review lies in its emphasis on the dual diagnostic–therapeutic role of nanoplatfroms in psychopathology, while also addressing ongoing challenges such as long-term safety, translational hurdles, large-scale manufacturing, and the integration of advanced imaging technologies for real-time disease monitoring [2, 7, 9].

PATHOPHYSIOLOGY OF PSYCHOPATHOLOGY AND NANOTHERAPEUTIC TARGETS

The pathophysiology of psychopathology involves complex neurobiological mechanisms that contribute to the development and progression of psychiatric disorders. These mechanisms include neurotransmitter imbalances, neuroinflammation, and synaptic dysfunction, which are critical in understanding the etiology of mental health conditions. Nanotherapeutics offer promising avenues for targeting these molecular pathways, potentially revolutionizing the treatment of psychiatric disorders. This section will explore the neurobiological mechanisms involved, identify molecular targets suitable for nanotherapeutics, and discuss the challenges and solutions related to the BBB in the context of nanoplatfroms.

Psychiatric disorders such as depression and schizophrenia are often associated with dysregulation of neurotransmitters like dopamine, serotonin, and glutamate. These imbalances can lead to altered synaptic transmission and contribute to the symptoms of these disorders [10].

Inflammatory processes, mediated by cytokines and glial cells, play a significant role in psychiatric conditions. Microglial activation, in particular, is a key factor in neuroinflammation, contributing to the pathophysiology of disorders like major depressive disorder (MDD) [11]. Alterations in synaptic plasticity and neuroplasticity are implicated in the development of psychiatric disorders. These changes can result from neurotransmitter imbalances and neuroinflammatory processes, affecting cognitive and emotional functions [9, 12].

[Rawani et al.] [13] Serotonin receptors are central to mood regulation and represent key pharmacological targets in the management of depressive and anxiety disorders, yet conventional agents often suffer from limited brain delivery and off-target effects (Rawani et al., 2024). Nanotherapeutic systems offer the potential to optimize these interventions by improving drug stability, enhancing penetration across the blood–brain barrier, and enabling receptor-specific targeting, thereby increasing therapeutic efficacy while minimizing adverse reactions.

Brain-derived neurotrophic factor (BDNF) plays a pivotal role in neuroplasticity, synaptic remodeling, and neuronal survival, and its dysregulation has been implicated in several psychiatric conditions characterized by impaired plasticity. By leveraging nanotechnology to deliver agents that upregulate or mimic BDNF signaling, it may be possible to more precisely restore synaptic function and improve clinical outcomes in disorders where conventional therapies fail to adequately modulate these pathways [12].

Microglia, as resident immune cells of the central nervous system, are critical mediators of neuroinflammation and have emerged as attractive targets for nano-enabled interventions in mood disorders such as major depressive disorder (MDD). Engineered nanoparticles can be designed to selectively interact with microglial cells, attenuating their pro-inflammatory activation profile and promoting a shift toward an anti-inflammatory, neuroprotective phenotype, which may alleviate inflammation-driven neurobiological alterations underlying MDD and related conditions [11, 14].

The BBB is a significant obstacle in delivering therapeutics to the brain, limiting the effectiveness of conventional treatments for psychiatric disorders [2]. Nanotechnology offers innovative solutions to overcome BBB challenges. Lipid nanoformulations and other nanoparticle-based systems can

enhance drug delivery across the BBB, improving bioavailability and targeting specific brain regions [2, 15]. These platforms allow for controlled and site-specific drug release, minimizing systemic side effects and enhancing therapeutic efficacy [9, 15].

While nanotherapeutics present exciting opportunities for advancing psychiatric treatment, it is essential to consider the broader implications and challenges. The long-term safety and potential bioaccumulation of nanoparticles in the brain remain areas of concern that require further research. Additionally, the complexity of psychiatric disorders necessitates a multifaceted approach, integrating nanotechnology with other therapeutic strategies to achieve optimal outcomes. As research progresses, the integration of nanotherapeutics into clinical practice could significantly enhance the precision and effectiveness of mental health treatments.

DESIGN AND BIOENGINEERING OF NANOPLATFORMS FOR MENTAL HEALTH

The design and bioengineering of nanoplatforms for mental health applications involve the classification of nanoplatforms, detailing engineering strategies, and comparing their properties. These nanoplatforms are pivotal in revolutionizing mental health diagnosis and treatment by enabling precise drug delivery and enhanced imaging capabilities. The following sections provide a comprehensive overview of the classification, engineering strategies, and properties of these nanoplatforms.

Nanoplatforms used in mental health applications are broadly categorized into organic, inorganic, and hybrid systems, each offering distinct structural and functional advantages for brain-targeted therapy. Organic nanocarriers, particularly lipid-based nanoparticles such as solid lipid nanoparticles and nanostructured lipid carriers, have been widely explored for improving the bioavailability and stability of psychotropic agents, including those used in schizophrenia, by protecting drugs from degradation and enhancing their capacity to reach central nervous system targets [16]. Similarly, polymeric nanoparticles constructed from biodegradable materials provide controlled and sustained drug release with improved physicochemical stability, making them especially suitable for long-term brain delivery strategies in chronic psychiatric disorders [17].

Inorganic nanoplatforms, typified by gold and

silica nanoparticles, contribute complementary capabilities to the nanomedicine toolkit through their unique physico-chemical properties, including tunable size, surface functionality, and, in the case of gold, distinctive optical behavior. These features underpin their use in both diagnostic imaging and therapeutic interventions, where they can serve as contrast agents, photothermal tools, or high-capacity carriers, and they are increasingly incorporated into multifunctional constructs for improved performance in neuropsychiatric contexts [18].

Hybrid systems integrate organic and inorganic components into a single platform, typically by embedding inorganic nanoparticles within organic nanocompartments to combine the biocompatibility and flexibility of organic carriers with the stability and functional versatility of inorganic cores. This design strategy can enhance colloidal stability, reduce toxicity, and enable simultaneous drug delivery and bioimaging, supporting the development of advanced theranostic systems tailored to the complex diagnostic and therapeutic needs of mental health disorders [18, 19].

The design of nanoplatforms for mental health applications increasingly relies on sophisticated engineering strategies, including surface functionalization, stimuli-responsiveness, and multifunctionality, to optimize both therapeutic and diagnostic performance. Surface modification with hydrophilic polymers such as polyethylene glycol (PEG) is widely used to prolong circulation time and reduce opsonization, thereby conferring “stealth” characteristics that help nanocarriers evade rapid clearance by the immune system [20]. In parallel, decorating nanoparticle surfaces with aptamers or other targeting ligands enables selective recognition of receptors at the blood–brain barrier and within specific neural or glial cell populations, improving brain penetration and enhancing the precision of drug delivery to relevant psychopathological circuits [20, 21].

Beyond passive and active targeting, stimuli-responsive designs introduce an additional layer of control by triggering drug release in response to local biochemical or physicochemical cues. Systems that respond to pH gradients or disease-associated enzymes can exploit the slightly acidic or enzyme-rich microenvironments present in certain brain regions or pathological niches, allowing on-demand liberation of therapeutic cargo while

limiting premature release in systemic circulation. Such context-sensitive behavior not only refines pharmacokinetic profiles but also helps to minimize off-target effects, an essential consideration in the treatment of complex psychiatric conditions where delicate neural networks are involved [22].

A further advancement in this field is the development of multifunctional nanoplateforms capable of combining therapeutic and diagnostic modalities within a single construct, thereby enabling true theranostic applications in mental health [9]. By co-loading drugs with imaging probes or contrast agents, these systems support simultaneous intervention and real-time monitoring of treatment response, facilitating more precise disease tracking and individualized dosing strategies. This convergence of targeting ligands, stimuli-responsive mechanisms, and integrated imaging elements positions engineered nanoplateforms as powerful tools for advancing personalized psychiatry and improving outcomes in disorders that have historically been difficult to manage with conventional approaches [9, 21].

The physicochemical properties of nanoplateforms particularly size, surface charge (zeta potential), and encapsulation efficiency are pivotal determinants of their behavior in the body and thus of their suitability for mental health applications. Organic nanocarriers such as lipid-based nanoparticles and polymeric systems commonly fall within the 10–200 nm range, a size window that favors prolonged circulation and supports effective traversal of biological barriers, whereas many inorganic and hybrid platforms are engineered on a slightly smaller scale, often between 1–100 nm, to exploit enhanced diffusivity and imaging [18, 19].

Zeta potential further influences colloidal stability, cellular interactions, and biodistribution, with organic nanoparticles typically exhibiting a net negative surface charge that can be strategically tuned through surface engineering to optimize brain targeting and minimize aggregation [17]. High encapsulation efficiency, which is frequently achieved in both organic and hybrid nanoplateforms, is essential for delivering therapeutically relevant drug loads while maintaining controlled release profiles, thereby enhancing treatment effectiveness in psychiatric indications where consistent target-site exposure is critical [16].

Despite these promising attributes, several obstacles still constrain the translation of

nanoplateforms into routine mental health practice, including uncertainties regarding long-term safety, the complexity of meeting regulatory requirements for advanced nanomedicines, and challenges related to reproducible, large-scale manufacturing [16, 23]. Addressing these issues will require the integration of sophisticated engineering approaches with a deeper, mechanistic understanding of how nanoplateform properties govern in vivo performance, ultimately enabling the rational design of safer, more effective systems for the diagnosis and treatment of psychiatric disorders [19].

NANOTHERAPEUTICS IN DIAGNOSIS OF PSYCHOPATHOLOGY

Nanotherapeutics have emerged as a promising frontier in the diagnosis of psychopathology, offering innovative solutions for early detection and monitoring of mental health disorders. These advanced technologies leverage the unique properties of nanoparticles to enhance diagnostic accuracy and provide real-time insights into the biochemical and structural changes associated with psychiatric conditions. The integration of nanotechnology in diagnostic applications is revolutionizing the field by enabling the detection of biomarkers, improving imaging techniques, and facilitating point-of-care diagnostics. The following sections explore the various diagnostic applications of nanotherapeutics in psychopathology.

Exosomes, small extracellular vesicles, are increasingly recognized as valuable biomarkers for neuropsychiatric diseases due to their ability to cross the blood-brain barrier and reflect the pathological state of the central nervous system. They contain proteins, lipids, and nucleic acids that can be indicative of disease states, making them a focus for diagnostic applications in psychopathology [24, 25]. Nanobiosensors have been developed to detect low concentrations of biomarkers in biological fluids, which are crucial for early diagnosis. These sensors are highly sensitive, cost-effective, and capable of real-time monitoring, making them ideal for detecting biomarkers like dopamine, which is critical in disorders such as depression and schizophrenia [26, 27].

IONPs are extensively used as MRI contrast agents due to their magnetic properties and biocompatibility. They enhance the quality of brain imaging by improving signal intensity and tissue retention, which is essential for diagnosing

neurological and psychiatric disorders [28]. SPIONs are particularly effective in functional neuroimaging, providing detailed insights into brain activity and aiding in the diagnosis of conditions like depression by highlighting areas of altered brain function [9, 29].

Lateral flow biosensors have emerged as practical tools for rapid, on-site detection of clinically relevant biomarkers, including exosomes and other circulating vesicles implicated in neuropsychiatric conditions, thereby supporting point-of-care decision-making in acute settings where time-sensitive interventions are required. By enabling simple, low-cost, and minimally instrumented analysis, these devices can assist clinicians in quickly assessing disease-related molecular changes, which may complement clinical evaluation during acute psychiatric episodes and facilitate more personalized management strategies [24]. Electrochemical biosensors provide a sensitive and specific platform for detecting neurotransmitters and additional biomarkers in cerebrospinal fluid and related biofluids, offering a less invasive and more responsive alternative to conventional laboratory-based diagnostic approaches. Their high analytical performance, coupled with the potential for miniaturization and integration into portable or implantable devices, makes them particularly attractive for continuous or repeated monitoring of neurochemical alterations associated with psychiatric disorders, thereby enhancing both diagnostic precision and treatment follow-up [30, 31]. While nanotherapeutics hold significant promise for advancing the diagnosis of psychopathology, there are challenges and considerations that must be addressed. The translation of these technologies from research to clinical practice requires rigorous validation and standardization to ensure safety and efficacy. Additionally, ethical considerations regarding the use of advanced diagnostic tools in mental health care must be carefully evaluated to prevent misuse and ensure equitable access. Despite these challenges, the potential of nanotechnology to transform mental health diagnostics remains substantial, offering hope for more precise and personalized approaches to managing psychiatric disorders.

NANOTHERAPEUTICS IN TREATMENT OF PSYCHOPATHOLOGY

The field of nanotherapeutics is revolutionizing the treatment of psychopathologies by offering innovative solutions for targeted drug delivery, gene

therapy, and neuromodulation. These advanced modalities aim to overcome the limitations of traditional therapies, such as BBB penetration and systemic side effects, thereby enhancing therapeutic efficacy and patient compliance. This answer explores the various therapeutic modalities and disease-specific applications of nanotherapeutics in psychopathology, supported by efficacy data from animal models and early trials.

Nanoparticles have been developed to enhance the delivery of antipsychotics like risperidone. For instance, clozapine-loaded lipid nanocapsules administered intranasally have shown improved brain bioavailability and reduced systemic side effects compared to oral and intravenous routes [32]. In schizophrenia, dopamine-modulating NPs have been explored to address the neurotransmitter imbalances characteristic of the disorder. These NPs facilitate targeted delivery across the BBB, improving therapeutic outcomes [33, 34].

Kumar et al., [9] found that gene therapy using siRNA encapsulated in NPs targets neuroinflammatory pathways, which are implicated in various psychiatric disorders. This approach holds promise for conditions like PTSD, where inflammation plays a critical role.

Kang et al., [35] reported that magnetic NPs are being investigated for their potential in neuromodulation, offering a non-invasive alternative to traditional deep brain stimulation techniques. These NPs can be directed to specific brain regions, providing precise therapeutic effects.

A study demonstrated the efficacy of VIPR2 antagonist encapsulated in NPs for treating schizophrenia. These NPs improved cognitive dysfunction in a mouse model, highlighting their potential as a novel therapeutic strategy [36]. Intranasal delivery of antipsychotics using nanosystems has shown promise in enhancing brain bioavailability and reducing adverse drug reactions, thereby improving patient compliance [34].

Liu et al., [22] reported that nanoencapsulation of selective serotonin reuptake inhibitors (SSRIs) has been explored to enhance their delivery and efficacy. Self-immolative nanocapsules delivering serotonin and catalase have shown synergistic effects in alleviating depressive symptoms in preclinical models. Also Kumar et al., [9] found that NPs targeting inflammatory pathways are being developed for PTSD, where neuroinflammation is a key pathological feature. These therapies aim

to modulate the immune response and improve clinical outcomes.

In a mouse model of schizophrenia, VIPR2 antagonist NPs demonstrated significant improvements in cognitive function, suggesting their potential for clinical application [35]. Nanoantidepressants have shown enhanced BBB penetration and therapeutic efficacy in animal models, offering a promising approach for treating depression [22]. While nanotherapeutics offer promising advancements in the treatment of psychopathologies, challenges remain in translating these findings from preclinical models to clinical practice. Issues such as long-term safety, large-scale production, and regulatory approval need to be addressed. Additionally, the complexity of psychiatric disorders necessitates a multifaceted approach, combining nanotechnology with other therapeutic strategies to achieve optimal outcomes. Nonetheless, the potential of nanotherapeutics to transform mental health treatment is undeniable, paving the way for more effective and personalized therapies.

THERANOSTIC NANOPLATFORMS: INTEGRATING DIAGNOSIS AND TREATMENT

The integration of “see-and-treat” platforms, which combine imaging technologies such as fluorescence with therapeutic modalities like photodynamic therapy (PDT), represents a significant advancement in the treatment of complex conditions such as gliosis. These platforms enable simultaneous diagnosis and treatment, enhancing the precision and effectiveness of medical interventions. The development of such theranostic agents is particularly promising in the context of brain diseases, where challenges like the BBB complicate treatment delivery. This approach is exemplified by the use of nanoparticles and other bioengineered platforms that facilitate targeted therapy and real-time monitoring.

PDT is a minimally invasive treatment that uses photosensitizers activated by light to produce reactive oxygen species, which can destroy targeted cells. When combined with imaging technologies such as near-infrared (NIR) optical imaging, magnetic resonance imaging (MRI), and positron emission tomography (PET), PDT can be used to both visualize and treat gliosis, allowing for personalized and precise interventions [37]. Multifunctional nanoparticles, such as those

incorporating indocyanine green (ICG) and paclitaxel, have been developed to target glioma cells. These nanoparticles can be activated by NIR light to provide both imaging and therapeutic functions, enhancing drug delivery and treatment efficacy through combined chemotherapy and hyperthermia [22, 37].

Exosome-mimetic nanoparticles have been engineered to deliver therapeutic agents across the BBB, providing real-time monitoring and drug release capabilities. For instance, nanoparticles loaded with curcumin and other therapeutic agents have shown promise in treating glioblastoma by enabling optical tracking and targeted drug delivery [38, 39]. Biomimetic nanoparticles, such as those using macrophage membranes, have been designed to enhance drug delivery and penetration in glioblastoma. These platforms utilize specific ligand-receptor interactions to improve targeting and treatment outcomes, demonstrating significant tumor suppression and increased survival rates in preclinical models [22, 40]. Platforms that integrate fluorescence and optoacoustic imaging with PDT have been developed to monitor and treat glioma. These systems allow for precise localization and treatment of tumors, improving therapeutic outcomes and reducing recurrence rates [41, 42].

While the integration of imaging and therapeutic technologies in “see-and-treat” platforms offers significant potential, challenges remain in translating these innovations from preclinical to clinical settings. Issues such as reproducibility, biocompatibility, and selective targeting need to be addressed to ensure the safe and effective application of these technologies in human patients. Additionally, the complexity of brain diseases like gliosis necessitates continued research and development to optimize these platforms for clinical use.

PRECLINICAL AND CLINICAL EVIDENCE

The section on “Preclinical and Clinical Evidence” in the review paper “Nanotherapeutics and Psychopathology: Revolutionizing Mental Health Diagnosis and Treatment with Bioengineered Nanoplatforms” should provide a comprehensive overview of the current state of research on nanoplatforms in mental health treatment. This includes summarizing key studies in a table format and analyzing the translational progress of these technologies from preclinical to clinical settings (Table 1).

Table 1. Key Studies Summary Table

Nanopatform Type	Target Disorder	Outcomes	Limitations
Black Phosphorus Nanosheets (BP-RVG29@HYP)	Depression	Improved bioavailability, reduced depressive-like behaviors, minimal adverse effects	Limited clinical data, potential long-term safety concerns [43].
Polymeric and Lipid-Based Nanocarriers	Alzheimer's Disease	Enhanced BBB penetration, reduced amyloid- β aggregation, improved cognitive outcomes	Long-term toxicity, regulatory challenges [44].
Nanocarrier Drug Delivery Systems	Depression	Increased bioavailability, reduced side effects, improved therapeutic efficacy	Scarcity of clinical trials, need for more research [1].
Metallic Nanoparticles (Gold, Silver)	Alzheimer's Disease	Targeted drug delivery, reduced oxidative stress	Reproducibility and scalability issues [44].
Nanoparticles for Catecholaminergic Drugs	Neuropsychiatric Disorders	Stabilized drug release, improved behavioral outcomes	Bioaccumulation, clinical feasibility concerns [15].

The transition from preclinical to clinical trials for nanoparticle-based antidepressants is still in its nascent stages. While preclinical studies have shown promising results in terms of enhanced drug delivery and efficacy, the clinical translation is hindered by challenges such as long-term safety, regulatory hurdles, and the need for robust clinical trial designs [45, 46]. Some progress has been made in translating nanotechnology for Alzheimer's treatment, with several nanocarriers showing potential in early-phase clinical trials. These trials focus on improving drug delivery across the BBB and reducing neurodegenerative markers, although large-scale trials are needed to confirm efficacy and safety [44, 45]. The clinical success of nanomedicines is often limited by pathophysiological complexities, variability in drug response, and manufacturing challenges. Addressing these issues requires a multidisciplinary approach and innovative trial designs to bridge the gap between preclinical findings and clinical applications [46].

While the potential of nanotherapeutics in mental health is significant, the path to clinical application is fraught with challenges. The complexity of psychiatric disorders, coupled with the intricacies of nanotechnology, necessitates a careful and methodical approach to research and development. Moreover, the regulatory landscape for nanomedicines is still evolving, which can impact the pace of clinical translation. Despite these hurdles, the integration of nanotechnology with personalized medicine and advanced diagnostic tools holds promise for revolutionizing mental health treatment in the future.

CHALLENGES AND SAFETY CONSIDERATIONS

The integration of nanotherapeutics in psychopathology presents a promising frontier

for revolutionizing mental health diagnosis and treatment. However, this field is fraught with challenges and safety considerations that must be addressed to ensure the safe and effective application of these technologies. Key issues include toxicity, immunogenicity, scalability, regulatory hurdles, and ethical concerns, particularly in neuropsychiatric applications. These challenges are critical to the development and clinical translation of nanomedicines.

Nanoparticles can accumulate in the brain, potentially leading to neurotoxicity. The mechanisms of NP breakdown and their long-term effects on brain tissue remain inadequately understood, posing significant safety concerns [47, 48]. The interaction of NPs with the immune system can lead to adverse immune responses. Ensuring biocompatibility and minimizing immunogenicity are crucial for the safe application of nanomedicines in the brain [49, 50].

The production of NPs at a scale suitable for clinical use presents significant challenges. Consistency in NP formulation and stability over time are critical for their successful integration into therapeutic regimens [49, 50]. Achieving uniformity in NP production is essential to ensure reproducibility and reliability in clinical applications. This requires advanced engineering techniques and stringent quality control measures [48].

The regulatory landscape for nanomedicines is complex and evolving. The FDA and other regulatory bodies need to establish clear guidelines that balance safety with innovation, avoiding both underregulation and overregulation [51-53]. Developing international standards for nanomedicine regulation is crucial to facilitate global clinical translation and ensure patient safety across different jurisdictions [54].

The use of brain-targeted therapies raises

ethical concerns regarding patient consent, particularly in vulnerable populations with mental health disorders. Ensuring informed consent and understanding of the potential risks and benefits is essential. The potential for non-medical applications of nanotechnologies in the brain, such as cognitive enhancement, poses ethical dilemmas. Public awareness and regulatory oversight are necessary to address these concerns [55].

While the potential of nanotherapeutics in psychopathology is immense, these challenges highlight the need for a cautious and well-regulated approach to their development and application. Addressing these issues through rigorous research, clear regulatory frameworks, and ethical considerations will be crucial to harnessing the full potential of nanomedicines in mental health care.

FUTURE PERSPECTIVES AND CONCLUSIONS

The convergence of advanced artificial intelligence and nanotechnology is poised to fundamentally reshape the future of healthcare, moving toward highly personalized, adaptive, and efficient therapeutic strategies. In particular, AI-driven optimization of nanoplatforms enables rational design of nanoparticles with precisely tuned properties, improving targeting, transport, and controlled drug release while reducing reliance on empirical trial-and-error approaches. At the same time, the integration of pharmacogenomic and molecular profiling into nanotherapeutic design supports truly individualized treatment regimens, aligning dose, formulation, and delivery route with each patient's unique genetic and physiological characteristics to maximize efficacy and minimize toxicity. Coupling these advances with wearable devices and nanosensors opens the door to closed-loop systems capable of continuous monitoring, early detection of clinically relevant changes, and real-time adjustment of therapy based on dynamic patient data. Realizing this vision will require close collaboration across disciplines to address technical, regulatory, and ethical challenges, including robust data integration, protection of patient privacy, mitigation of bias in AI models, and equitable access to these emerging technologies. If these hurdles are thoughtfully managed, AI-enabled, personalized nanomedicine supported by connected digital health tools has the potential to transform patient care from reactive and generalized to proactive, precise, and responsive.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this manuscript. All authors have disclosed any financial or personal relationships that could potentially influence or bias the work presented.

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