Frontline Medical Sciences and Pharmaceutical Journal
ISSN: 2752-6712

Emerging Therapeutics in Neuropharmacology: Innovations in Drug Delivery and Targeted Treatment of Neurodegenerative Disorders

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ARTICLE INfO

Articlehistory:
Submission Date:29February2026
Accepted Date:22March2026
Published Date:01April2026
VOLUME: Vol.06 Issue04
Page No. 11-15

ABSTRACT

Neurodegenerative disorders, including Alzheimer's disease, Parkinson's disease, and amyotrophic lateral sclerosis, pose major clinical challenges due to progressive neuronal loss, limited regenerative capacity, and poor therapeutic penetration across the blood-brain barrier (BBB) (Kumar et al., 2021; Chen et al., 2020). Recent advances in neuropharmacology have emphasized innovative drug delivery systems, including nanoparticles, liposomes, exosomes, and polymeric carriers, to enhance BBB penetration and achieve targeted delivery to affected brain regions (Singh & Patel, 2022). Precision-guided pharmacotherapy leveraging genetic and proteomic biomarkers allows patient-specific interventions, improving therapeutic efficacy and minimizing adverse effects. Preclinical platforms, including 3D organotypic brain cultures, microfluidic neurochips, and human induced pluripotent stem cell-derived neuronal networks, provide physiologically relevant models for evaluating drug response, toxicity, and neuroregenerative potential (Li et al., 2021). This review synthesizes current strategies in neuropharmacology, highlighting the integration of advanced drug carriers, precision medicine, and bioengineered platforms. Challenges such as immunogenicity, long-term neurotoxicity, and clinical translation barriers are discussed, and future directions including theranostic approaches, AI-assisted drug design, and combinatorial neurotherapeutics are proposed. The convergence of these multidisciplinary strategies offers a transformative potential to optimize treatment outcomes and slow disease progression in neurodegenerative disorders.

Keywords:- Neurodegenerative disorders, Blood-brain barrier, Nanoparticles, Precision pharmacotherapy, Bioengineered models, Targeted delivery, Neuroregeneration

INTRODUCTION

Neurodegenerative disorders are characterized by progressive neuronal loss, synaptic dysfunction, and cognitive or motor impairment, leading to substantial morbidity and healthcare burden globally. Despite extensive research, effective therapeutic options remain limited due to challenges in drug delivery across the BBB, neurotoxicity, and heterogeneity of disease

pathophysiology (Kumar et al., 2021). Traditional small-molecule therapies often exhibit poor solubility, rapid clearance, and off-target effects, reducing clinical efficacy and patient adherence.

Innovative Drug Delivery Strategies: Recent developments in nanomedicine have introduced lipid-based nanoparticles, polymeric micelles, dendrimers, exosomes, and hybrid carriers capable of crossing the BBB and delivering drugs directly to affected neuronal populations. Surface functionalization with ligands such as transferrin, peptides, and aptamers facilitates receptor-mediated transport, improving targeted accumulation while minimizing systemic exposure (Singh & Patel, 2022). Stimuli-responsive systems allow controlled release in response to pH, oxidative stress, or enzymatic activity within diseased brain regions.

Precision Pharmacotherapy: Advances in genomics and proteomics provide biomarker-guided strategies for individualized treatment. Genetic variants, protein aggregation profiles, and metabolic markers can inform dosage, combination therapy, and drug selection, enhancing efficacy while reducing neurotoxicity (Chen et al., 2020). Personalized neuropharmacology allows stratification of patients based on predicted responsiveness, particularly in Alzheimer's and Parkinson's disease.

Bioengineered Preclinical Models: Traditional animal models often fail to recapitulate human neurophysiology and disease progression. Emerging 3D organotypic brain cultures, neurochips, and iPSC-derived neuronal networks provide physiologically relevant platforms for testing drug penetration, efficacy, and toxicity (Li et al., 2021). These models enable high-throughput evaluation of novel therapeutics and combinatorial interventions, facilitating translation into clinical trials.

Challenges: Immunogenicity, long-term safety of nanoparticle carriers, variability in BBB permeability, and regulatory hurdles remain substantial barriers. Ethical considerations related to patient-derived neuronal models and genomic profiling also require careful governance.

This review aims to provide a comprehensive synthesis of contemporary strategies in neuropharmacology, integrating advanced drug delivery systems, precision-guided interventions, and bioengineered evaluation platforms. Emphasis is placed on translational potential, therapeutic optimization, and future directions to enhance treatment efficacy and patient outcomes.

REVIEW OF LITERATURE

Emerging therapeutics in neuropharmacology have gained substantial attention due to the increasing global burden of neurodegenerative disorders such as Alzheimer's Disease, Parkinson's Disease, and Amyotrophic Lateral Sclerosis. Traditional pharmacological approaches often face significant limitations, including poor drug permeability across the blood–brain barrier (BBB), non-specific targeting, and limited therapeutic efficacy. Recent literature highlights innovative drug delivery systems and targeted therapeutic strategies as promising solutions to these challenges.

One of the most notable advancements is the development of nanotechnology-based delivery systems designed to cross the BBB effectively. Nanocarriers such as solid lipid nanoparticles, polymeric nanoparticles, and liposomes have demonstrated the ability to enhance drug bioavailability and facilitate targeted delivery to specific brain regions. These systems can be engineered with surface modifications, such as ligand attachment, enabling receptor-mediated transport across the BBB.

Additionally, intranasal drug delivery has emerged as a non-invasive and efficient route for brain targeting. Studies suggest that this method bypasses the BBB via the olfactory and trigeminal nerve pathways, allowing direct drug transport to the central nervous system. This approach has shown potential in improving therapeutic outcomes in neurodegenerative conditions.

Targeted treatment strategies, including gene therapy, stem cell therapy, and monoclonal antibody-based interventions, are also gaining prominence. Monoclonal antibodies, for instance, are being explored for their ability to selectively target pathological proteins such as beta-amyloid plaques in Alzheimer's disease. Similarly, gene-editing tools and neuroprotective agents are being investigated to slow disease progression at the molecular level.

Furthermore, advancements in controlled-release formulations and biomaterials have enabled sustained drug delivery within the brain, reducing dosing frequency and enhancing patient compliance.

Overall, the literature indicates that innovations in drug delivery and targeted therapies are revolutionizing neuropharmacology, offering new hope for effective management of neurodegenerative disorders, though further clinical validation remains essential.

RESEARCH METHODOLOGY

This review employed a systematic literature synthesis to analyze current advances in neuropharmacology, focusing on drug delivery, targeted therapeutics, and bioengineered evaluation models for neurodegenerative disorders. Databases searched included PubMed, Scopus, Web of Science, and ScienceDirect, with publications from 2015 to 2025 considered. Keywords used were "neurodegenerative disorders," "blood-brain barrier drug delivery," "nanoparticles for neurotherapy," "precision pharmacotherapy," "iPSC neuronal models," and "organ-on-chip brain models."

Inclusion criteria:

1. Original research articles detailing nanoparticle, liposomal, dendrimer, exosome, or hybrid drug delivery systems for neurodegenerative disease therapy.
2. Studies incorporating biomarker-guided, patient-specific pharmacotherapy strategies.
3. Preclinical studies using 3D organotypic brain cultures, neurochips, or iPSC-derived neuronal networks for drug testing.

Exclusion criteria:

- Narrative reviews without experimental data
- Studies not focused on chronic neurodegenerative diseases
- Research lacking methodological rigor

Data extraction focused on drug penetration efficiency across the BBB, targeted delivery success, neuroprotective outcomes, adverse effects, and translational potential. Comparative analyses were conducted to identify trends, gaps, and emerging technologies, while ensuring the synthesis adhered to high scientific standards (Kumar et al., 2021; Chen et al., 2020).

RESULTS

1. Advanced Drug Delivery Systems

Lipid-Based Nanoparticles and LiposomesThese carriers demonstrated enhanced blood-brain barrier penetration, increased drug half-life, and reduced systemic toxicity. Functionalization with transferrin, lactoferrin, or peptide ligands enabled receptor-mediated transport, targeting neurons and glial cells (Singh & Patel, 2022). Preclinical studies reported improved cognitive function and reduced neuroinflammation in Alzheimer's and Parkinson's disease models.

Polymeric Carriers and Micelles: Biodegradable polymers such as PLGA and PEG-PLA allowed controlled drug release and sustained neuronal exposure, which is crucial for slow-progressing neurodegenerative disorders. Polymeric micelles encapsulating hydrophobic neuroprotective drugs demonstrated enhanced stability and bioavailability, supporting long-term therapeutic interventions (Li et al., 2021).

Exosomes and Hybrid Carriers: Exosome-based delivery provided intrinsic targeting capability and minimal immunogenicity. Hybrid carriers combining lipid, polymer, and exosomal features further improved BBB penetration and targeted accumulation, showing promising efficacy in preclinical models of ALS and Huntington's disease.

2. Precision Pharmacotherapy

Genetic and proteomic profiling facilitated patient-specific interventions, optimizing drug selection, dosing, and combination therapies. Biomarkers such as APOE4 genotype, alpha-synuclein aggregation levels, and tau protein isoforms guided therapy in Alzheimer's and Parkinson's disease (Chen et al., 2020). These strategies reduced adverse events, enhanced cognitive and motor outcomes, and improved therapeutic adherence.

3. Bioengineered Preclinical Models

3D Organotypic Brain Cultures: These models maintained neuronal architecture and synaptic connectivity, enabling evaluation of drug penetration, neuroprotection, and toxicity. Drugs delivered via nanoparticles showed improved uptake and efficacy compared to conventional 2D cultures (Kumar et al., 2021).

Neurochips and Microfluidic Systems: Neurochips provided controlled microenvironments for neuronal networks, allowing precise assessment of electrophysiological responses to drugs. They enabled high-throughput screening and modeling of neurodegenerative disease progression.

iPSC-Derived Neuronal Networks: Human iPSC-derived neurons recapitulated patient-specific pathology, allowing personalized drug testing.

Nanoparticle-mediated therapies exhibited improved neuronal survival, reduced protein aggregation, and enhanced synaptic function, demonstrating translational relevance.

4. Translational Insights

Integration of advanced carriers with precision-guided therapy and bioengineered models has accelerated the preclinical evaluation of neurodegenerative therapeutics. Early-phase clinical trials of lipid nanoparticles, polymeric micelles, and exosome-based drugs reported improved drug bioavailability and therapeutic response, with manageable safety profiles. Challenges persist in scaling production, ensuring reproducibility, and monitoring long-term neurotoxicity, but ongoing research provides promising pathways for clinical translation (Singh & Patel, 2022; Li et al., 2021).

DISCUSSION

The integration of advanced drug delivery systems, precision pharmacotherapy, and bioengineered preclinical models represents a significant advancement in the management of neurodegenerative disorders. Lipid nanoparticles, polymeric micelles, dendrimers, and exosome-based carriers provide enhanced BBB penetration, targeted neuronal delivery, and controlled drug release, overcoming the primary barriers of conventional therapies (Singh & Patel, 2022; Kumar et al., 2021). Functionalization with ligands for receptor-mediated transport ensures selective targeting of neurons or glial cells, reducing off-target toxicity and improving therapeutic outcomes.

Precision Pharmacotherapy: Genetic, proteomic, and metabolomic profiling enables patient-specific interventions, tailoring drug selection, combination therapy, and dosage. Biomarkers such as APOE4 genotype, tau protein isoforms, and alpha-synuclein aggregation guide therapeutic strategies, enhancing efficacy while minimizing adverse effects (Chen et al., 2020). Integration of these strategies promotes a personalized medicine paradigm in neurodegenerative disease management.

Bioengineered Preclinical Models: 3D organotypic brain cultures, neurochips, and iPSC-derived neuronal networks provide highly predictive models that replicate human neurophysiology. These platforms enable precise evaluation of drug penetration, neuroprotective effects, and synaptic restoration, bridging the gap between preclinical studies and clinical translation (Li et al., 2021). High-throughput screening of nanoparticle-based therapeutics in these systems accelerates drug optimization and identification of combinatorial strategies.

Challenges and Limitations: Despite these advances, long-term neurotoxicity, immunogenicity of novel carriers, variability in BBB permeability, and regulatory hurdles remain substantial barriers. Ethical concerns regarding patient-derived neuronal models, genetic data use, and accessibility must also be addressed. Translating these innovations into scalable, clinically viable interventions requires careful consideration of safety, reproducibility, and cost-effectiveness.

Future Directions: Emerging theranostic platforms, AI-assisted drug design, and combinatorial neurotherapies offer promising opportunities to enhance treatment precision. Integration of patient-specific biomarkers with advanced delivery systems could allow adaptive therapy, modifying interventions based on disease progression and therapeutic response. Multi-disciplinary collaboration among neuroscientists, bioengineers, pharmacologists, and regulatory agencies will be critical to realize the full potential of personalized neuropharmacology.

CONCLUSION

The convergence of innovative drug carriers, precision pharmacotherapy, and bioengineered preclinical models provides transformative potential for neurodegenerative disease management. Nanoparticle-based, liposomal, polymeric, and exosome-mediated delivery systems enhance BBB penetration, targeted drug

accumulation, and sustained therapeutic effects. Precision medicine approaches, guided by genetic and proteomic biomarkers, allow patient-specific optimization of therapies, improving efficacy and safety. Bioengineered platforms such as 3D organotypic cultures, neurochips, and iPSC-derived neuronal networks provide physiologically relevant, translationally predictive models for preclinical evaluation.

Despite challenges in long-term safety, scalability, and regulatory compliance, the synergistic application of these strategies offers a paradigm shift toward personalized, precise, and effective neurotherapeutics. Future innovations combining AI-driven drug design, theranostic platforms, and combinatorial therapy are expected to further improve patient outcomes and slow disease progression, ushering in a new era in neuropharmacology.

REFERENCES

1. Chen, L., Zhang, Y., & Wang, H. (2020). Biomarker-guided precision medicine in neurodegenerative disorders. Frontiers in Neuroscience, 14, 567–580.

2. Kumar, S., Patel, R., & Li, X. (2021). Advanced nanoparticle-mediated drug delivery systems for neurodegenerative diseases. Journal of Controlled Release, 337, 456–474.

3. Li, X., Singh, A., & Tanaka, H. (2021). Bioengineered preclinical models in neuropharmacology: Applications and translational perspectives. ACS Biomaterials Science & Engineering, 7(8), 3290–3308.

4. Singh, A., Patel, R., & Chen, L. (2022). Emerging strategies in targeted neurotherapeutics: Liposomes, micelles, and exosomes. Neurotherapeutics, 19(3), 1012–1030.

5. Tanaka, H., Li, X., & Kumar, S. (2022). Precision-guided pharmacotherapy in neurodegenerative disorders: Opportunities and challenges. Frontiers in Pharmacology, 13, 789123.

6. Zhou, H., Wang, J., & Singh, A. (2021). Stimuli-responsive drug delivery systems for central nervous system disorders. Journal of Nanobiotechnology, 19, 280–295.

7. Sharma, P., Verma, N., & Gupta, R. (2023). Nanocarrier-based targeted delivery approaches in neurodegenerative disease therapy. International Journal of Pharmaceutics, 635, 122678.

8. Mehta, D., Kaur, G., & Singh, S. (2022). Role of lipid-based nanocarriers in brain-targeted drug delivery. Drug Delivery and Translational Research, 12(5), 1123–1140.

9. Brown, T., Wilson, M., & Anderson, K. (2023). Advances in monoclonal antibody therapies for neurodegenerative disorders. Neuroscience Letters, 785, 136812.

10. Gupta, A., Nair, R., & Das, P. (2021). Intranasal drug delivery systems for brain targeting: A review of recent advancements. European Journal of Pharmaceutical Sciences, 159, 105712.