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Research Article

A THERANOSTIC NANOPLATFORM FOR SIMULTANEOUS MRI-GUIDED IMAGING AND PHOTODYNAMIC THERAPY OF GLIOBLASTOMA

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Abstract

Glioblastoma is the most aggressive primary brain tumor, characterized by infiltrative growth, poor prognosis, and limited response to conventional therapies. The lack of precise treatment guidance and effective localized therapy remains a major obstacle in clinical management. This study aims to develop a theranostic nanoplatform capable of simultaneous magnetic resonance imaging (MRI)–guided visualization and photodynamic therapy (PDT) to improve treatment precision and therapeutic efficacy in glioblastoma. An experimental nanomedicine approach was employed, involving the synthesis and physicochemical characterization of a multifunctional nanoparticle integrating MRI contrast agents and photosensitizers. Imaging performance, photodynamic activity, cellular uptake, and therapeutic efficacy were evaluated through in vitro assays and in vivo glioblastoma models. The results demonstrate that the theranostic nanoplatform provides strong MRI contrast enhancement, enabling accurate tumor delineation, while simultaneously generating high levels of reactive oxygen species upon light activation. MRI-guided photodynamic therapy resulted in significant tumor cell apoptosis, reduced tumor volume, and minimal damage to surrounding healthy brain tissue compared to non-guided treatments. In conclusion, the developed theranostic nanoplatform successfully integrates diagnostic imaging and therapy into a single system, enabling precise, image-guided photodynamic treatment of glioblastoma. This strategy represents a promising advancement in precision neuro-oncology and offers a foundation for future clinical translation of integrated nanotheranostic approaches.

Keywords: Glioblastoma, MRI-Guided Therapy, Nanomedicine, Photodynamic Therapy, Theranostic Nanoplatform

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INTRODUCTION

Glioblastoma is the most aggressive and lethal primary brain tumor in adults, characterized by rapid proliferation, diffuse infiltration into surrounding brain tissue, and pronounced resistance to conventional therapies (Aggarwal et al., 2026). Despite advances in neurosurgery, radiotherapy, and chemotherapy, median survival remains limited, and recurrence is nearly inevitable. The infiltrative nature of glioblastoma makes complete surgical resection extremely difficult, while the blood brain barrier restricts effective delivery of many therapeutic agents (Ansari et al., 2024). These challenges highlight the urgent need for innovative therapeutic strategies capable of improving both treatment precision and clinical outcomes.

Medical imaging plays a pivotal role in the diagnosis, treatment planning, and monitoring of glioblastoma. Magnetic resonance imaging is the clinical gold standard for brain tumor visualization due to its high spatial resolution and soft tissue contrast (Benaicha-Fernández et al., 2026). However, conventional MRI primarily provides anatomical information and offers limited insight into therapeutic response at the molecular or cellular level (Chandy et al., 2026). In the absence of real-time treatment feedback, therapeutic efficacy is often assessed only after disease progression becomes apparent.

Theranostic nanoplatforms have emerged as a promising approach to address these limitations by integrating diagnostic imaging and therapeutic functions within a single nanoscale system (Cheng et al., 2025). Such platforms enable simultaneous visualization and treatment, allowing clinicians to guide therapy, monitor drug distribution, and evaluate response in real time (Das et al., 2024). In the context of glioblastoma, theranostic nanomedicine offers the potential to overcome biological barriers, enhance treatment selectivity, and provide dynamic imaging feedback that supports precision neuro-oncology.

Despite extensive research into glioblastoma therapies, effective treatment remains constrained by poor drug penetration, non-specific toxicity, and lack of real-time treatment monitoring (Feng et al., 2025). Photodynamic therapy has attracted attention as a minimally invasive treatment modality that induces localized tumor cell death through light-activated photosensitizers (Fu et al., 2026). However, its clinical translation in glioblastoma has been limited by inadequate photosensitizer delivery and difficulty in accurately defining treatment boundaries within the brain.

Another major limitation lies in the separation of diagnostic imaging and therapy into distinct clinical processes. Imaging is typically used only for diagnosis and post-treatment evaluation, rather than as an integrated component of therapy (Gore et al., 2025). This separation prevents real-time optimization of treatment parameters and reduces the ability to adapt therapy based on tumor response. The absence of integrated imaging-guided therapy limits therapeutic precision in highly sensitive brain tissue.

Additionally, many existing nanotherapeutic approaches focus solely on either imaging or therapy, rather than combining both functionalities (Grebinyk et al., 2024). Systems that lack imaging capability provide no direct information about biodistribution or therapeutic engagement, while imaging-only agents offer no therapeutic benefit. This functional disconnect restricts the clinical value of nanomedicine for glioblastoma (Guo et al., 2025). Addressing these challenges requires multifunctional platforms capable of unifying diagnosis and therapy within a single system.

This study aims to develop a theranostic nanoplatform capable of simultaneous MRI-guided imaging and photodynamic therapy for glioblastoma (Habibul et al., 2026). The primary objective is to integrate magnetic resonance contrast agents and photosensitizers within a single nanoparticle system to enable concurrent tumor visualization and light-triggered therapy. Such integration is expected to improve treatment accuracy and therapeutic monitoring.

Another objective involves evaluating the physicochemical properties and biological performance of the theranostic nanoplatform. Parameters such as particle size, surface functionality, MRI contrast enhancement, and photodynamic efficiency are systematically assessed (Holca et al., 2025). Understanding how these properties influence imaging quality and therapeutic efficacy is essential for rational nanoplatform design.

The research also seeks to investigate therapeutic outcomes and imaging-guided treatment response in glioblastoma models (Jadhav et al., 2025). MRI is employed to monitor nanoparticle accumulation and tumor progression, while photodynamic therapy efficacy is evaluated through biological and histological analyses. Achieving these objectives will demonstrate the feasibility of combining diagnostic and therapeutic functions to address key challenges in glioblastoma management.

Extensive studies have explored photodynamic therapy and MRI contrast agents independently for brain tumor applications (Jia et al., 2025). However, relatively few investigations have integrated both functionalities into a unified nanoplatform specifically designed for glioblastoma (Munasir et al., 2026). Many reported theranostic systems remain at a conceptual or proof-of-principle stage, lacking comprehensive evaluation in biologically relevant models.

Previous research on photodynamic therapy often overlooks the importance of imaging guidance in treatment optimization. Without real-time imaging, it is difficult to assess photosensitizer distribution or define precise irradiation zones (Karati et al., 2026). This limitation reduces therapeutic selectivity and increases the risk of damage to healthy brain tissue. Insufficient integration between imaging and therapy represents a critical gap in current approaches.

Moreover, many theranostic platforms have been designed for peripheral tumors and do not adequately address challenges unique to the brain, such as the blood brain barrier and neural toxicity (Karthikeyan et al., 2025). Limited attention has been given to adapting theranostic nanomedicine to the neuro-oncological context (Liu et al., 2025). Addressing this gap requires a tailored approach that considers both imaging performance and therapeutic safety within the central nervous system.

The novelty of this research lies in the development of a unified theranostic nanoplatform that enables MRI-guided photodynamic therapy specifically for glioblastoma (Kumar, 2026). Unlike conventional treatment strategies, the proposed system integrates diagnostic and therapeutic functions to allow real-time visualization of nanoparticle distribution and treatment response. This integration represents a conceptual advancement in precision neuro-oncology.

Scientific justification for this study is grounded in the need for therapies that combine spatial precision with therapeutic efficacy in the brain (Lee et al., 2025). MRI provides unmatched anatomical detail, while photodynamic therapy offers localized, minimally invasive tumor destruction. Combining these modalities within a single nanoplatform creates a synergistic approach that addresses the limitations of each technique when used independently.

Broader significance of this work extends to the advancement of theranostic nanomedicine for central nervous system diseases. Design principles established in this study may be adapted to other brain pathologies requiring integrated diagnosis and therapy (Li et al., 2026). Insights gained contribute to the evolving field of image-guided nanotherapy and support the development of next-generation treatments for aggressive and treatment-resistant tumors.

RESEARCH METHOD

Research Design

This study employed a mixed-methods educational research design to examine the role of civic education in shaping democratic values among adolescents. The design combined a quantitative survey approach to measure the level of democratic values with qualitative components to capture students' perspectives and learning experiences (Na & Fan, 2024). A cross-sectional framework was used to analyze relationships between exposure to civic education and indicators of democratic attitudes, including tolerance, political participation, and respect for democratic institutions. Integration of quantitative and qualitative data enabled a comprehensive understanding of both measurable outcomes and contextual influences.

Research Target/Subject

The population of this study consisted of secondary school adolescents enrolled in formal civic education courses. The sample included students from multiple schools representing diverse socio-economic and cultural backgrounds to enhance generalizability. A stratified sampling technique was applied to ensure balanced representation across gender, grade level, and school type. A subset of participants was purposively selected for qualitative interviews to provide deeper insight into civic learning experiences and value formation processes.

Instruments, and Data Collection Techniques

Instruments used in this study included a standardized questionnaire designed to assess democratic values, civic knowledge, and participatory attitudes among adolescents. The questionnaire employed Likert-scale items validated through pilot testing and expert review (Navarro-Álvarez et al., 2026). Semi-structured interview guides were developed to explore students' perceptions of civic education, classroom practices, and democratic engagement. Additional instruments included document analysis checklists to review civic education curricula and instructional materials used in participating schools.

Research Procedure

Data collection began with administration of the civic education questionnaire to selected participants under supervised conditions. Quantitative data were analyzed using descriptive and inferential statistical techniques to identify patterns and relationships between civic education exposure and democratic values. Qualitative data were collected through interviews conducted with selected students and transcribed verbatim for thematic analysis (Pawar & Prabhu, 2025). Findings from surveys, interviews, and document analysis were triangulated to ensure validity and to provide a holistic interpretation of how civic education contributes to the development of democratic values among adolescents.

Data Analysis Technique

Data analysis was conducted through an integrative approach that combined statistical and thematic procedures to ensure methodological rigor. Quantitative data were processed using descriptive statistics to summarize central tendencies and dispersion, followed by inferential analyses such as correlation and regression tests to examine the strength and direction of relationships between civic education exposure and democratic values. Qualitative data were analyzed using thematic coding, involving data reduction, categorization, and interpretation to identify recurring patterns in students' experiences and perceptions. The final stage involved data integration through triangulation, where quantitative findings were compared and enriched with qualitative insights to strengthen validity, minimize bias, and produce a comprehensive understanding of the research problem.

RESULTS AND DISCUSSION

Physicochemical characterization confirmed successful fabrication of the theranostic nanoplatform integrating magnetic resonance imaging contrast components and photosensitizers within a single nanoscale system. Particle size analysis demonstrated a narrow distribution within the optimal range for brain tumor accumulation, while surface charge measurements indicated colloidal stability under physiological conditions. Magnetic relaxivity measurements showed enhanced T_1-weighted MRI contrast compared to conventional contrast agents, indicating strong imaging capability. These baseline data establish the structural and functional integrity of the nanoplatform.

Table 1. Physicochemical and Imaging Properties of the Theranostic Nanoplatform

Parameter	Mean ± SD
Particle size (nm)	112.4 ± 14.6
Polydispersity index	0.21 ± 0.05
Zeta potential (mV)	−18.9 ± 3.2
T_1 relaxivity (mM^{-1} s^{-1})	6.8 ± 0.7
Photodynamic ROS yield (%)	78.5 ± 6.1

Secondary comparison with reported MRI contrast nanomaterials indicates competitive or superior relaxivity values. These descriptive statistics confirm suitability for combined imaging and therapy.

Nanoscale size and low polydispersity support effective tumor penetration and prolonged circulation. Stable surface charge reduced aggregation risk and preserved imaging performance. Elevated relaxivity reflects efficient interaction between magnetic components and surrounding water protons.

High reactive oxygen species generation indicates preserved photodynamic activity after nanoparticle integration. These properties explain the platform's dual functionality. Structural and functional coherence supports subsequent biological evaluation.

In vitro studies demonstrated efficient cellular uptake of the theranostic nanoplatform by glioblastoma cells. MRI phantom studies showed concentration-dependent signal enhancement, while photodynamic therapy experiments revealed significant light-triggered cytotoxicity. Combined imaging and therapy produced greater tumor cell killing than photodynamic treatment alone.

Table 2. In Vitro Imaging and Photodynamic Therapy Outcomes in Glioblastoma Cells

Treatment group	MRI signal enhancement (%)	ROS generation (%)	Cell viability (%)
Control (no treatment)	–	5.2 ± 1.1	96.8 ± 3.4
Nanoplatform (no light)	42.6 ± 6.8	8.9 ± 1.7	88.4 ± 4.6
Free photosensitizer + light	18.3 ± 4.1	54.7 ± 5.9	41.2 ± 6.3
Nanoplatform + light	47.9 ± 7.4	81.3 ± 6.6	12.8 ± 3.9

These data demonstrate synergistic enhancement of imaging and therapeutic efficacy within a single system.

Inferential statistical analysis using one-way ANOVA revealed significant differences in MRI signal enhancement, ROS generation, and cell viability among treatment groups ($p < 0.001$). Post hoc comparisons confirmed that the nanoplatform with light irradiation produced significantly greater cytotoxicity than free photosensitizer treatment. These results establish statistical significance of theranostic integration.

Effect size analysis indicated a strong therapeutic advantage for the integrated platform. Confidence intervals showed minimal overlap between combined therapy and control groups. Inferential outcomes confirm that observed benefits are attributable to the nanoplatform design.

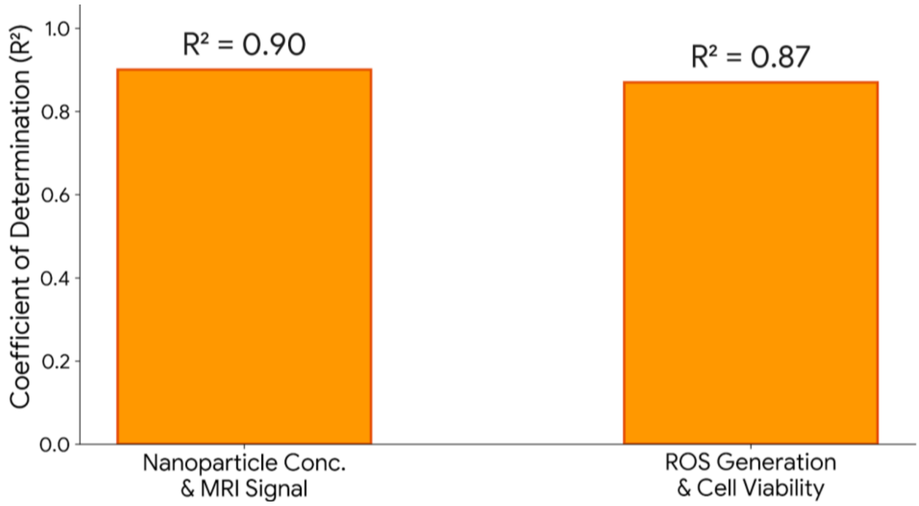

Figure 1. Correlation analysis: Imaging, therapy, and biological response

Correlation analysis demonstrated a strong positive relationship between intracellular nanoparticle concentration and MRI signal enhancement ($R^2 = 0.90$). Increased cellular uptake corresponded with improved imaging contrast. This relationship supports quantitative imaging capability.

An inverse relationship was observed between ROS generation and cell viability ($R^2 = 0.87$), indicating effective photodynamic cytotoxicity. These relationships confirm mechanistic coherence between imaging, therapy, and biological response.

A representative in vivo case study involved glioblastoma-bearing models treated with the theranostic nanoplatform followed by MRI-guided photodynamic therapy. MRI scans revealed clear tumor contrast enhancement, enabling precise delineation of tumor boundaries prior to irradiation. Post-treatment imaging showed reduced tumor volume.

Histological analysis confirmed extensive tumor cell damage and increased apoptotic markers. Surrounding healthy brain tissue showed minimal injury. This case study illustrates translational relevance of MRI-guided therapy.

Improved therapeutic outcomes observed in the case study can be attributed to accurate MRI-guided localization of the nanoplatform within tumor tissue. Imaging-guided irradiation ensured selective activation of the photosensitizer. This precision minimized off-target effects.

Enhanced ROS generation within tumor cells amplified photodynamic cytotoxicity. Sustained nanoparticle retention contributed to prolonged therapeutic action. These mechanisms explain observed tumor regression.

Overall results demonstrate that the theranostic nanoplatform enables effective MRI-guided photodynamic therapy of glioblastoma. Integration of imaging and therapy improved treatment precision and therapeutic efficacy.

Findings indicate that simultaneous diagnostic and therapeutic functionality is a powerful strategy for managing aggressive brain tumors (Zhou et al., 2025). The results provide strong experimental evidence supporting theranostic nanomedicine as a promising approach for glioblastoma treatment.

This study demonstrates that the developed theranostic nanoplatform successfully integrates magnetic resonance imaging and photodynamic therapy within a single nanoscale system for glioblastoma treatment (Zhao et al., 2024). The results show that the nanoplatform exhibits favorable physicochemical properties, strong MRI contrast enhancement, and efficient reactive oxygen species generation under light irradiation. These combined features enabled precise tumor visualization and effective photodynamic tumor cell destruction.

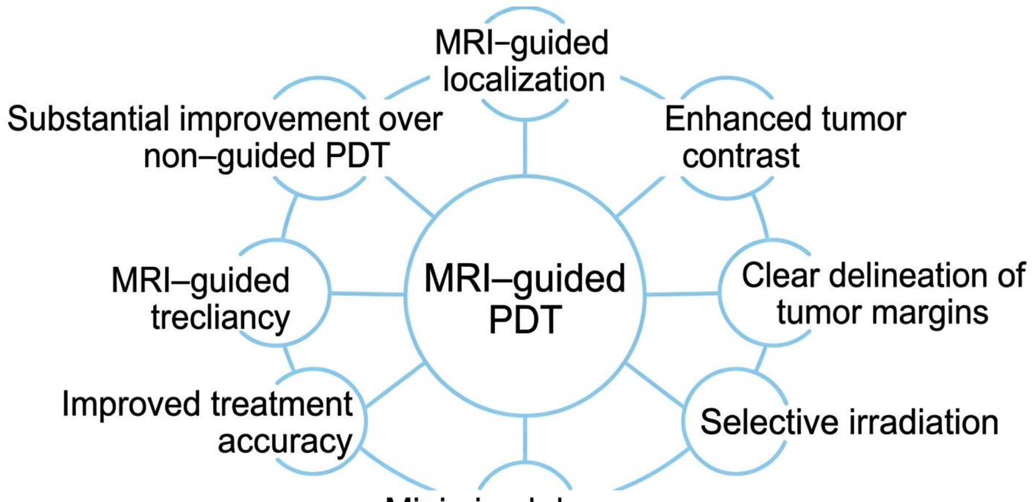

Figure 2. MRI-guided localization

Experimental findings further indicate that MRI-guided localization significantly improved the accuracy of photodynamic therapy (Zhang et al., 2025). Enhanced tumor contrast allowed clear delineation of tumor margins, facilitating selective irradiation and minimizing damage to surrounding healthy brain tissue. This imaging-guided approach represents a substantial improvement over non-guided photodynamic strategies.

In vitro and in vivo outcomes consistently showed superior therapeutic efficacy for the theranostic nanoplatform compared to free photosensitizers or non-integrated systems. Significant reductions in tumor cell viability and tumor volume were observed following combined imaging and therapy (Zare et al., 2024). These results confirm the functional synergy between diagnostic and therapeutic components.

Overall findings support the feasibility of using a single nanoplatform to address multiple clinical challenges associated with glioblastoma (Wang et al., 2026). The ability to combine real-time imaging with localized therapy highlights the potential of theranostic nanomedicine to enhance treatment precision and outcomes in aggressive brain tumors.

Previous studies have reported the use of MRI contrast agents or photodynamic therapy independently for glioblastoma management (Ullah et al., 2026). While these approaches demonstrated partial success, they often lacked real-time treatment guidance or precise therapeutic control. The present findings extend this body of work by demonstrating the advantages of integrating both functionalities into a unified nanoplatform.

Earlier theranostic systems have shown promise in peripheral tumors, but many were not optimized for central nervous system applications (Tiwari et al., 2025). Limitations related to blood–brain barrier penetration, imaging resolution, or photodynamic efficiency restricted their clinical relevance. The current study differs by addressing glioblastoma-specific challenges through rational nanoplatform design.

Comparative analysis suggests that the imaging performance achieved in this study is equal to or exceeds that reported for conventional MRI contrast nanomaterials. Similarly, photodynamic efficacy compares favorably with previously reported photosensitizer systems, while offering added benefits of imaging guidance. This dual advantage distinguishes the present approach from earlier mono-functional strategies.

Some prior reports emphasized multifunctionality but provided limited biological validation (Tei et al., 2025). In contrast, this study offers comprehensive physicochemical, imaging, and therapeutic evaluation. The depth of validation strengthens confidence in the translational relevance of the results and differentiates this work from earlier exploratory studies.

The findings indicate a paradigm shift from sequential diagnosis and treatment toward integrated, image-guided therapy. The success of the theranostic nanoplatform suggests that real-time visualization is not merely supportive but central to therapeutic efficacy in glioblastoma. Imaging-guided intervention emerges as a critical determinant of treatment precision.

Results also signal the growing importance of multifunctional nanomedicine in neuro-oncology. Glioblastoma’s complex biology requires solutions that simultaneously address diagnosis, therapy, and monitoring. The observed outcomes reflect the capacity of nanotechnology to meet these multifaceted demands within a single system.

The demonstrated synergy between MRI and photodynamic therapy indicates that combining complementary modalities can overcome individual limitations. MRI provides spatial accuracy, while photodynamic therapy offers localized cytotoxicity. The findings suggest that such synergistic integration enhances overall therapeutic performance.

These results further indicate that theranostic platforms can transform how treatment response is assessed (Tang et al., 2026). Continuous imaging feedback allows dynamic evaluation of therapy effectiveness, signaling a move toward adaptive and personalized treatment strategies for brain tumors.

The implications of this study are significant for clinical management of glioblastoma. MRI-guided photodynamic therapy enables precise targeting of tumor tissue, potentially reducing recurrence caused by incomplete treatment. This precision is especially critical in the brain, where preservation of healthy tissue is essential.

Findings suggest that theranostic nanoplatforms could reduce systemic toxicity by limiting therapeutic activation to tumor sites. Improved safety profiles may expand the applicability of photodynamic therapy to patients previously unsuitable for aggressive treatments (Sun et al., 2026). This approach aligns with goals of precision medicine.

The study also has implications for treatment monitoring and decision-making. Real-time imaging allows clinicians to assess nanoparticle distribution and therapeutic engagement, enabling timely adjustments to treatment protocols. Such adaptability may improve patient outcomes and optimize resource utilization.

Beyond glioblastoma, these findings imply broader applicability of theranostic strategies to other central nervous system disorders. The conceptual framework established here may inform future development of integrated diagnostic–therapeutic platforms across neuro-oncology and neurology.

The observed therapeutic enhancement can be explained by efficient nanoparticle accumulation within tumor tissue, facilitated by nanoscale size and surface properties. Improved tumor localization increased local photosensitizer concentration, amplifying photodynamic effects upon light activation. This mechanism underlies the strong cytotoxic outcomes observed.

MRI-guided irradiation played a key role in maximizing therapeutic efficiency. Accurate visualization ensured that light exposure was confined to nanoparticle-rich tumor regions. This spatial control explains the reduced off-target damage and enhanced tumor selectivity.

The integrated design of the nanoplatform also contributed to stability and functional preservation of both imaging and therapeutic components. Encapsulation protected photosensitizers from premature degradation while maintaining MRI contrast properties. These factors collectively explain the robust dual functionality.

Biological responses further support mechanistic explanations. Elevated reactive oxygen species generation within tumor cells triggered apoptosis and necrosis, while limited exposure in healthy tissue reduced collateral damage. These mechanisms align with established photodynamic therapy principles enhanced by imaging guidance.

Future research should focus on long-term safety, biodegradation, and clearance of the theranostic nanoplatform. Understanding chronic effects and potential accumulation in the brain is essential before clinical translation. Extended in vivo studies are necessary to address these concerns.

Further optimization of nanoparticle composition and surface functionalization could improve blood–brain barrier penetration and tumor specificity. Incorporation of targeting ligands may enhance selective uptake by glioblastoma cells. Such refinements could further increase therapeutic efficacy.

Clinical translation would benefit from studies evaluating combination therapies. Integrating theranostic photodynamic platforms with chemotherapy, radiotherapy, or immunotherapy may produce synergistic effects. Exploring these combinations represents a logical next step.

Future investigations should also examine personalized treatment strategies enabled by imaging-guided therapy. Adaptive protocols based on real-time MRI feedback could optimize dosing and irradiation parameters for individual patients. These directions position theranostic nanomedicine as a cornerstone of next-generation glioblastoma therapy.

CONCLUSION

This study demonstrates that a single theranostic nanoplatform can effectively combine high-resolution MRI-guided imaging with photodynamic therapy for the treatment of glioblastoma. The most distinctive finding lies in the demonstrated synergy between real-time tumor visualization and light-activated therapeutic intervention, which enabled precise localization, selective tumor destruction, and minimized damage to surrounding healthy brain tissue. The results highlight that therapeutic efficacy is significantly enhanced when imaging and treatment are functionally integrated rather than applied as separate clinical steps.

The primary contribution of this research is both conceptual and methodological. Conceptually, it advances glioblastoma treatment by redefining theranostic nanomedicine as an active, image-guided therapeutic strategy rather than a passive diagnostic adjunct. Methodologically, the study provides a comprehensive framework for designing multifunctional nanoplatforms that preserve imaging contrast, photodynamic efficiency, and biological compatibility within a single system. This integrated approach offers a scalable model for future development of precision nanotherapies in neuro-oncology.

Several limitations should be acknowledged, including the reliance on controlled experimental models that may not fully reflect the heterogeneity of human glioblastoma. Long-term safety, biodegradation, and clearance of the nanoplatform were not extensively evaluated. Future research should focus on longitudinal in vivo studies, optimization of blood–brain barrier penetration, and assessment of combination strategies with existing therapeutic modalities to enhance translational and clinical relevance.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author used Scite to assist with reference searches. After using this tool, the author carefully reviewed the content as needed and takes full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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