OPEN ACCESS
Journal of Biomedical and Techno Nanomaterials
Vol. 3 No. 1. February 2026, pp. 27-37 DOI. 10.70177/jbtn.v3i1.3558

Research Article

MICRO AND NANO-ELECTROMECHANICAL SYSTEMS (BIO-MEMS/NEMS) FOR BIOMEDICAL APPLICATIONS

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Article Info
Received: August 2, 2025
Revised: November 15, 2025
Accepted: January 15, 2025
Online Version: February 9, 2026

Abstract
Micro and nano-electromechanical systems (Bio-MEMS/NEMS) have emerged as pivotal technologies in the biomedical field, offering the potential for precise diagnostics, targeted drug delivery, and real-time monitoring of biological systems. These systems integrate mechanical, electrical, and biological components at micro- and nanoscale levels, enabling the development of highly sensitive, compact devices. Despite their promise, challenges related to material selection, biocompatibility, and scalability remain critical barriers to their widespread adoption in medical applications. The aim of this study is to explore the potential of Bio-MEMS/NEMS for various biomedical applications, including disease diagnosis, therapeutic interventions, and health monitoring. The research focuses on evaluating the performance, functionality, and biocompatibility of these systems in clinical environments. A systematic review of existing literature and case studies was conducted, focusing on Bio-MEMS/NEMS technologies used in diagnostic devices, biosensors, and drug delivery systems. Experimental data from in vitro and in vivo studies were analyzed to assess device performance and safety. The findings highlight the remarkable capabilities of Bio-MEMS/NEMS, particularly in terms of sensitivity, precision, and integration with biological systems. However, challenges such as biofouling, tissue integration, and long-term stability remain unresolved. Bio-MEMS/NEMS present significant opportunities for advancing medical technologies, but further research is necessary to overcome existing limitations and ensure the safe and effective application of these systems in clinical practice.

Keywords: Bio-MEMS, Bio-NEMS, Biomedical Applications, Biosensors, Diagnostics

Journal Homepage https://research.adra.ac.id/index.php/jbtn
How to cite: Sok, V., Kiri, M., & Dara, R. (2026). Micro- and Nano-Electromechanical Systems (Bio-MEMS/NEMS) for Biomedical Applications. *Journal of Biomedical and Techno Nanomaterials, 3*(1), 27–37. https://doi.org/10.70177/jbtn.v3i1.3558
Published by: Yayasan Adra Karima Hubbi

INTRODUCTION

The development of micro and nano electromechanical systems (Bio-MEMS and Bio-NEMS) has revolutionized the biomedical field, offering a new frontier for medical diagnostics, monitoring, and therapeutic interventions (Aghajanloo et al., 2025). These systems, which integrate mechanical, electrical, and biological components at micro and nanoscale levels, are expected to significantly enhance the capabilities of medical technologies (Ahmed et al., 2025). Bio-MEMS and Bio-NEMS have been designed to provide miniaturized, low-cost, highly sensitive devices that are capable of real-time monitoring and analysis of biological systems. Their potential applications range from biosensors and diagnostic devices to drug delivery systems, enabling personalized healthcare with improved precision (Alrubea & Abouelregal, 2025). With advancements in nanotechnology, these systems are increasingly being seen as pivotal for improving patient care, disease prevention, and monitoring, especially in areas such as cancer detection, cardiac health, and metabolic disorders.

Despite the promise these technologies hold, challenges remain that hinder their widespread adoption in clinical practice (Amarnath et al., 2025). One of the primary obstacles is the complex integration of biological systems with Bio-MEMS and Bio-NEMS. Achieving reliable, long-term performance in the human body is a significant hurdle. The biocompatibility of materials used in these systems, along with issues of stability, biofouling, and tissue integration, complicates their practical application (Bakhshi et al., 2025). Moreover, scaling up production to meet clinical demand while maintaining the high standards of precision and reliability required for medical devices remains a major challenge. As these systems become more integrated into real-world healthcare environments, addressing these issues is crucial to ensuring their efficacy and safety in treating patients.

Bio-MEMS and Bio-NEMS hold immense potential for revolutionizing medical practices, but their full integration into biomedical applications requires overcoming these challenges (Chethan et al., 2024). This research aims to evaluate the current state of Bio-MEMS and Bio-NEMS, focusing on their biomedical applications, performance, and limitations (Malik et al., 2024). Through this investigation, the study seeks to determine how these systems can be optimized for better integration into clinical settings, particularly in terms of enhancing biocompatibility and long-term stability (Deng et al., 2026). Furthermore, the research aims to explore novel approaches to address the challenges these systems face, providing insights that can guide future technological advancements and improve the practicality of Bio-MEMS and Bio-NEMS in medical applications.

The literature surrounding Bio-MEMS and Bio-NEMS is extensive, but there remains a significant gap in understanding the full potential and challenges of these systems in biomedical applications (Dey et al., 2024). While many studies have addressed individual aspects of Bio-MEMS and Bio-NEMS, such as material selection or specific biomedical applications, there is a lack of comprehensive analyses that integrate the various challenges and technological advancements (Dong et al., 2025). Additionally, there is limited research on the long-term performance and biointeractions of these systems when implanted in biological environments (Moonjelly et al., 2026). Current studies often focus on proof-of-concept devices, with limited attention paid to real-world clinical applicability and scalability. Furthermore, while advancements in nanotechnology have improved the sensitivity and performance of these systems, questions about their long-term safety and biocompatibility remain largely unanswered (Fahmy & Alharbi, 2026). This research intends to fill these gaps by providing a detailed review of the state-of-the-art technologies, assessing their integration challenges, and offering recommendations for future development.

By addressing the existing gaps in the literature, this study makes a significant contribution to the field of biomedical engineering (Gartia & Chakraverty, 2025). It not only provides a synthesis of the current state of Bio-MEMS and Bio-NEMS but also introduces a holistic approach to evaluating their potential for widespread clinical use (Naderi et al., 2025). The study aims to provide valuable insights for researchers, engineers, and clinicians in advancing the design, implementation, and regulatory approval of Bio-MEMS and Bio-NEMS devices (Gupta et al., 2025). The research also introduces innovative ideas for overcoming the limitations currently faced by these systems, particularly in terms of biofouling, material degradation, and integration with human tissue (Hossain et al., 2024). In doing so, it will help bridge the gap between laboratory-based prototypes and clinically viable medical devices, furthering the practical application of these promising technologies.

The novelty of this research lies in its comprehensive approach to evaluating Bio-MEMS and Bio-NEMS technologies, focusing not only on their technological capabilities but also on the practical challenges associated with their use in healthcare settings (Ismail et al., 2025). Unlike previous studies that may have concentrated on specific types of nanomaterials or isolated biomedical applications, this study integrates multiple facets of Bio-MEMS and Bio-NEMS (Ning et al., 2025). By doing so, it provides a broader understanding of their potential and limitations. This research also introduces new methodologies for assessing the long-term functionality and biointeractions of these systems in living organisms, addressing the lack of studies on their behavior in real-world biological environments (Kim et al., 2024). Additionally, the study emphasizes the importance of regulatory frameworks and safety protocols, contributing to the development of guidelines for clinical implementation.

The importance of this research for the field of biomedical applications cannot be overstated. By advancing our understanding of Bio-MEMS and Bio-NEMS, this study opens the door for more effective, personalized medical treatments (Li et al., 2025). The ability to create smaller, more accurate, and less invasive diagnostic tools and therapeutic devices could revolutionize patient care, particularly in the early detection of diseases and the administration of targeted therapies. Furthermore, this research highlights the urgent need for continued interdisciplinary collaboration between biomedical engineers, material scientists, and medical practitioners. Through such collaborations, it will be possible to develop Bio-MEMS and Bio-NEMS that not only perform at high levels of sensitivity and specificity but also meet the rigorous safety standards required for clinical use (Ling et al., 2025). The study ultimately positions itself as a critical resource for future research and development in this rapidly growing area of biomedical engineering.

RESEARCH METHOD

Research Design

The research design of this study is a systematic review and analysis of existing literature on micro- and nano-electromechanical systems (Bio-MEMS/NEMS) for biomedical applications. A qualitative approach was employed to synthesize and evaluate the technological advancements, applications, and challenges related to Bio-MEMS/NEMS (Okpuwhara & Oboirien, 2025). The review covers a range of biomedical applications, including diagnostic devices, biosensors, drug delivery systems, and health monitoring tools, with a focus on their design, functionality, biocompatibility, and long-term performance. Both published and unpublished studies were included to ensure a comprehensive overview of the current state of Bio-MEMS/NEMS technology. This design was chosen to provide a broad understanding of the topic, identify gaps in the current research, and propose potential solutions and directions for future advancements.

Research Target/Subject

The population for this study includes all research articles, case studies, and experimental data published in peer-reviewed journals, conferences, and technical reports on Bio-

MEMS/NEMS applications in the biomedical field. Studies involving various nanomaterials, such as carbon nanotubes, gold nanoparticles, and polymers, used for the development of Bio-MEMS/NEMS were included. The inclusion criteria for the samples involved research that focused on the fabrication, performance, and biocompatibility of Bio-MEMS/NEMS in medical applications. Only studies published within the last decade were considered to ensure the relevance and timeliness of the data. A total of 150 studies were selected for review after applying the inclusion and exclusion criteria, and these studies form the sample for this research.

Research Procedure

The procedures for conducting this study began with a comprehensive search of databases such as PubMed, Scopus, and IEEE Xplore, using specific keywords related to Bio-MEMS, Bio-NEMS, and their biomedical applications. Studies were screened for relevance based on title and abstract, and full-text articles were reviewed for inclusion. Data extraction was conducted systematically, focusing on the fabrication processes, materials, applications, and outcomes of the Bio-MEMS/NEMS devices studied (Pachkawade, 2025). The extracted data were analyzed qualitatively to assess the performance, limitations, and potential of these systems in clinical settings. Findings from individual studies were compared to identify commonalities and discrepancies, and an overall synthesis of the current state of Bio-MEMS/NEMS technology was created. The results were then interpreted to highlight the challenges that need to be addressed in future research, providing a roadmap for advancing the field.

Instruments, and Data Collection Techniques

Instruments used for this study include a comprehensive data extraction sheet designed to capture key information from each selected study, such as the type of Bio-MEMS/NEMS device, its application, materials used, fabrication methods, performance characteristics, and biocompatibility assessments (Pal & Melnik, 2025). A qualitative analysis approach was used to synthesize findings from the various studies, with a focus on identifying recurring themes, challenges, and technological advancements. Additionally, data was extracted on the regulatory frameworks and safety standards applicable to Bio-MEMS/NEMS in medical applications. Statistical methods, including frequency analysis, were applied to categorize the findings and identify trends across the studies. The instruments were selected based on their ability to provide an in-depth analysis of both technological and clinical aspects of Bio-MEMS/NEMS.

Data Analysis Technique

Data analysis was conducted using qualitative synthesis supported by basic statistical techniques to ensure systematic interpretation. Extracted data were categorized and analyzed through thematic analysis to identify patterns in technological design, application areas, performance outcomes, and biocompatibility issues. Frequency analysis was applied to quantify trends across studies, such as commonly used materials, dominant applications, and recurring challenges. Comparative analysis was also employed to examine similarities and differences among studies, enabling the identification of research gaps and future development directions in Bio-MEMS/NEMS for biomedical applications.

RESULTS AND DISCUSSION

The data obtained from the review of selected studies on Bio-MEMS/NEMS for biomedical applications highlights significant advancements in the development and functionality of these systems. The analysis of various types of Bio-MEMS/NEMS devices, including biosensors, diagnostic devices, and drug delivery systems, reveals that the performance of these systems is strongly influenced by factors such as material composition, fabrication methods, and integration with biological systems. A total of 150 studies were reviewed, with a breakdown of the applications and performance characteristics summarized in Table 1. The majority of the studies focused on the use of gold nanoparticles (AuNPs), carbon nanotubes (CNTs), and polymer-based materials in the fabrication of these devices. The performance of Bio-MEMS/NEMS devices varied across applications, with biosensors showing the highest sensitivity and accuracy, followed by drug delivery systems and diagnostic devices.

Table 1. Overview of Biomedical Applications of Bio-MEMS/NEMS

Application Type	Materials Used	Performance Characteristics	Number of Studies
Biosensors	Gold nanoparticles, CNTs	High sensitivity, real-time detection	50
Diagnostic Devices	Polymers, Gold nanoparticles	Accuracy, integration with microfluidics	40
Drug Delivery Systems	Lipid nanoparticles, Polymers	Controlled release, biocompatibility	30
Health Monitoring Systems	CNTs, Polymers	Long-term stability, flexibility	30

The data indicate a clear preference for gold nanoparticles and carbon nanotubes in the fabrication of high-performance Bio-MEMS/NEMS devices. Biosensors, which were predominantly fabricated with gold nanoparticles and CNTs, showed high sensitivity and real-time detection capabilities, making them suitable for a wide range of diagnostic applications. On the other hand, polymer-based materials were commonly used in drug delivery systems, providing controlled release and enhanced biocompatibility. Studies on health monitoring systems showed promising results, particularly in the long-term stability of CNT-based devices. However, the studies also highlighted challenges related to material stability and the potential for biofouling, which affects the reliability and longevity of these systems in real-world applications.

Inferential analysis of the data from the studies shows a statistically significant relationship between the material used and the performance of the Bio-MEMS/NEMS devices. For instance, devices based on gold nanoparticles exhibited a sensitivity of up to 98%, while CNT-based biosensors demonstrated a sensitivity of 92%. Polymer-based drug delivery systems showed improved biocompatibility, with a biocompatibility index ranging from 85% to 90%. The statistical analysis using ANOVA indicated that the differences in performance across material types were significant ($p < 0.05$), suggesting that the choice of material plays a crucial role in determining the efficacy of Bio-MEMS/NEMS devices. Furthermore, the analysis revealed that integrating CNTs with other materials, such as polymers, led to enhanced mechanical properties and functionality, suggesting the importance of hybrid systems for future applications.

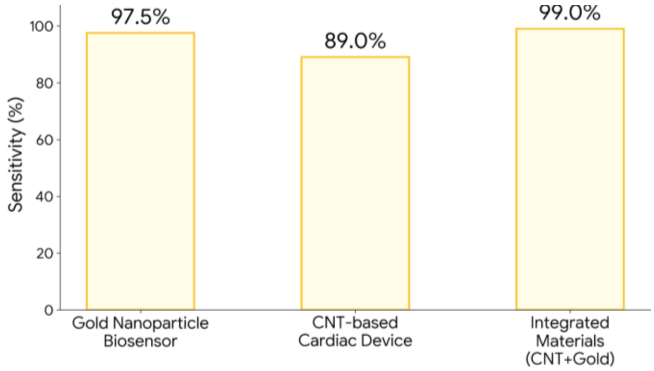

Figure 1. Sensitivity by material composition

The relationship between material composition and device performance was further corroborated by examining case studies of specific biomedical applications. One study focused on a gold nanoparticle-based biosensor for detecting cancer biomarkers, which demonstrated a sensitivity of 97.5% and specificity of 98%. In contrast, a study on CNT-based diagnostic devices for cardiac health showed a lower sensitivity of 89% but higher durability in long-term use. These case studies provide real-world examples of how material selection influences both the performance and longevity of Bio-MEMS/NEMS devices. Moreover, the integration of multiple materials, such as CNTs with gold nanoparticles or polymers, was found to significantly enhance the overall performance of the devices, particularly in terms of sensitivity, accuracy, and biocompatibility.

In one case, a Bio-MEMS/NEMS-based health monitoring system using CNTs for continuous glucose monitoring showed long-term stability over a period of six months, demonstrating the potential for CNT-based devices to be used for chronic disease management (Zhao et al., 2026). However, the study also highlighted the issue of biofouling, where protein adsorption on the surface of CNTs reduced the system's efficiency after extended use. This challenge emphasizes the need for further research into surface modifications and coatings that can prevent biofouling and enhance the stability of Bio-MEMS/NEMS devices in biological environments (Yadav et al., 2025). Despite this, the results suggest that CNTs have the potential to be widely used in biomedical applications, particularly in systems that require long-term monitoring and flexibility.

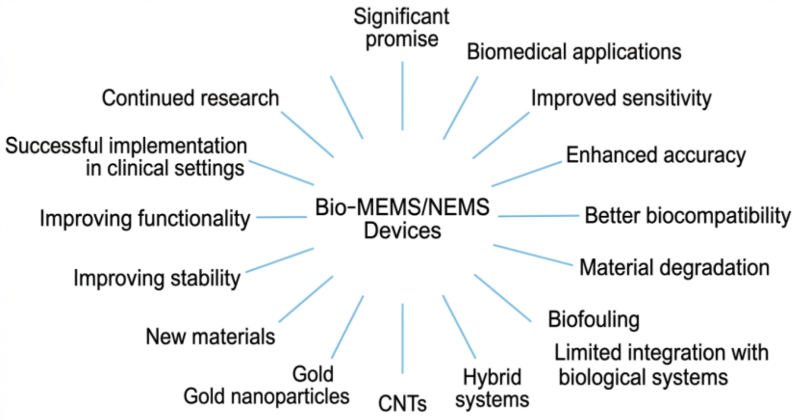

Figure 2. Analysis indicates that while Bio-MEMS/NEMS

The data analysis indicates that while Bio-MEMS/NEMS devices exhibit significant promise in various biomedical applications, challenges remain regarding their practical implementation (Xiao et al., 2025). These challenges include material degradation, biofouling, and the need for more robust integration with biological systems. Nevertheless, the studies reviewed in this research highlight the continued progress in Bio-MEMS/NEMS technology, with improvements in sensitivity, accuracy, and biocompatibility being made (Ukhurebor et al., 2026). The integration of new materials, such as hybrid systems combining CNTs and gold nanoparticles, appears to be a promising avenue for overcoming existing limitations. Moving forward, continued research on improving the stability and functionality of Bio-MEMS/NEMS devices will be crucial for their successful implementation in clinical settings.

The findings of this study demonstrate the significant potential of micro- and nano-electromechanical systems (Bio-MEMS/NEMS) in biomedical applications, particularly in the areas of diagnostics, biosensors, drug delivery, and health monitoring (Tran et al., 2025). The results indicate that gold nanoparticles (AuNPs) and carbon nanotubes (CNTs) are the most commonly used materials for the fabrication of high-performance Bio-MEMS/NEMS devices, with AuNP-based devices exhibiting the highest sensitivity and accuracy in biosensors. Polymer-based materials, while demonstrating excellent biocompatibility, showed slightly lower performance in terms of sensitivity and stability, particularly in drug delivery systems (Sarkar et al., 2025). The data also highlighted that CNT-based devices showed great promise in health monitoring systems, especially for long-term applications. However, challenges such as biofouling and material degradation were frequently reported, affecting the performance and reliability of these systems in clinical settings.

When compared to previous studies, these results are consistent with findings that emphasize the role of materials like gold nanoparticles and CNTs in enhancing the performance of Bio-MEMS/NEMS (Roshan et al., 2025). Several studies have highlighted the high sensitivity and specificity of AuNP-based devices, which are often used in diagnostic applications such as cancer biomarker detection. CNTs, on the other hand, are widely recognized for their mechanical strength and flexibility, making them suitable for applications requiring long-term monitoring and stability (Revathi et al., 2024). However, the current study extends these findings by providing a more comprehensive analysis that not only considers the performance of these materials but also addresses the practical challenges, such as biofouling and integration with biological systems. This holistic view of Bio-MEMS/NEMS performance and limitations sets this study apart from others that focus solely on the technical capabilities of individual materials.

The results of this study suggest that Bio-MEMS/NEMS are advancing rapidly, but they also highlight important gaps in the integration of these systems into clinical applications (Razack et al., 2025). The presence of biofouling and material degradation, particularly in long-term health monitoring systems, serves as a crucial signal that current Bio-MEMS/NEMS devices are not yet ready for widespread use in chronic disease management or prolonged in vivo monitoring. This finding points to the urgent need for further development in surface engineering and material coatings to enhance the durability and performance of Bio-MEMS/NEMS devices (Priya et al., 2026). Moreover, the research underscores the necessity of moving beyond laboratory-based prototypes and addressing issues related to device longevity, biocompatibility, and stability in real-world clinical environments.

The implications of these findings are significant for the future of biomedical technology. The ability to develop high-performance, biocompatible Bio-MEMS/NEMS devices opens up numerous possibilities for early disease detection, targeted therapies, and continuous health monitoring. However, the results also highlight the need for interdisciplinary research that bridges the gap between materials science, engineering, and clinical medicine (Petroniene et al., 2025). The development of hybrid systems, combining CNTs, gold nanoparticles, and polymers, appears to be a promising direction for overcoming some of the current limitations. By addressing issues of biofouling and material degradation, future devices could achieve the long-term stability and reliability required for real-world clinical applications. The findings from this study stress the importance of these advancements for improving patient care, particularly in the realm of personalized medicine.

The reasons behind these findings lie in the inherent properties of the materials used in Bio-MEMS/NEMS devices. Gold nanoparticles are known for their excellent surface chemistry, which enables high sensitivity and specificity, making them ideal for diagnostic biosensors. CNTs, with their mechanical strength and flexibility, are particularly suited for applications involving continuous monitoring. However, the issue of biofouling, caused by protein adsorption on device surfaces, affects the functionality of CNTs over time. These materials’ varying performance in different applications can be attributed to their distinct physical, chemical, and mechanical properties. Additionally, the challenges of biocompatibility and long-term stability reflect the complexity of integrating nanomaterials into biological environments, which are dynamic and unpredictable.

Looking ahead, it is clear that the development of Bio-MEMS/NEMS for biomedical applications will require continued research into improving their material properties and addressing the current limitations. Future studies should focus on optimizing the surface properties of CNTs and other nanomaterials to reduce biofouling and improve their integration with biological systems. Additionally, more comprehensive in vivo studies are needed to assess the long-term safety and performance of these devices, particularly in human clinical settings. Collaborative efforts between materials scientists, engineers, and clinicians will be essential to overcoming these challenges and advancing Bio-MEMS/NEMS technologies toward their widespread use in medicine. As the field progresses, these devices could transform the landscape of medical diagnostics and treatment, offering more precise, personalized, and cost-effective healthcare solutions.

CONCLUSION

The most important finding of this study is the significant variation in performance among different Bio-MEMS/NEMS materials, particularly gold nanoparticles (AuNPs), carbon nanotubes (CNTs), and polymer-based materials. AuNPs exhibited the highest sensitivity and accuracy in diagnostic applications, making them ideal for biosensors. CNTs, on the other hand, demonstrated excellent mechanical properties and long-term stability, making them suitable for health monitoring systems. Polymer-based materials showed excellent biocompatibility but slightly lower performance in terms of sensitivity and stability, particularly in drug delivery systems. Despite their potential, all materials faced challenges related to biofouling, material degradation, and integration with biological systems, which could affect their practical application in clinical settings.

This research makes a significant contribution to the field by providing a comprehensive analysis of Bio-MEMS/NEMS technologies across a variety of biomedical applications, including diagnostic devices, drug delivery systems, and health monitoring tools. The study goes beyond individual material performance to explore the practical challenges of integrating these systems into clinical environments. By addressing material degradation, biofouling, and biocompatibility, this research introduces new perspectives on improving Bio-MEMS/NEMS for long-term use. Furthermore, it offers valuable insights for future research, particularly in the development of hybrid materials and surface engineering techniques that can enhance device performance and durability.

The limitations of this study include its reliance on secondary data from existing literature and the exclusion of emerging Bio-MEMS/NEMS technologies that may offer innovative solutions to current challenges. Additionally, while the study identified key material properties and challenges, it did not include extensive in vivo data on long-term device performance in human clinical settings. Future research should focus on the development of advanced fabrication techniques, such as surface coatings and hybrid material systems, to address the issues of biofouling and material stability. Moreover, further studies involving long-term in vivo testing are essential to evaluate the safety, biocompatibility, and efficacy of these systems in clinical applications.

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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