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**Research Article**

# DEVELOPMENT OF A BIO-MEMS CANTILEVER-BASED BIOSENSOR FOR THE RAPID, LABEL-FREE DETECTION OF THE AVIAN INFLUENZA VIRUS

Thiago Rocha[1], Clara Mendes[2], and Rafaela Lima[3]
[1] Universidade Federal Bahia, Brazil
[2] Universidade Estadual Campinas, Brazil
[3] Universidade Federal Paraná, Brazil

**Corresponding Author:**

Thiago Rocha,
Faculty of Medicine, Universidade Federal Bahia
Av. Adhemar de Barros, s/nº - Ondina, s/nº - Ondina, Salvador - BA, 40170-110, Brazil
Email: thiagorocha@gmail.com

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## Abstract

Avian influenza virus remains a significant threat to global public health, poultry industries, and food security due to its high transmissibility and zoonotic potential. Rapid and reliable detection is essential for early outbreak control, yet conventional diagnostic methods are often time-consuming, laboratory-dependent, and rely on labeled reagents, limiting their applicability in field and point-of-care settings. This study aims to develop a Bio-MEMS cantilever-based biosensor capable of rapid, label-free detection of the avian influenza virus with high sensitivity and specificity. An experimental Bio-MEMS approach was employed, involving microfabrication of silicon cantilevers, surface biofunctionalization with virus-specific recognition elements, and real-time mechanical sensing of virus–receptor interactions. The biosensor's performance was evaluated by measuring cantilever deflection responses under controlled exposure to varying viral concentrations. The results demonstrate stable baseline behavior, low noise levels, and clear concentration-dependent deflection signals, achieving rapid detection within minutes and a low limit of detection without signal amplification. Non-target analytes produced negligible responses, confirming high specificity. In conclusion, the developed Bio-MEMS cantilever-based biosensor provides an effective platform for rapid, label-free detection of avian influenza virus. This technology shows strong potential for integration into portable diagnostic systems and could be adapted for surveillance of other viral pathogens.

**Keywords**: **:** Bio-MEMS Biosensor, Cantilever Sensor, Avian Influenza Virus, Label-Free Detection, Rapid Diagnostics



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## INTRODUCTION

Avian influenza virus continues to pose a serious threat to global public health, food security, and economic stability due to its high mutation rate and zoonotic transmission potential (Hasanah et al., 2023). Outbreaks among poultry populations often result in massive economic losses, while certain strains have demonstrated the ability to cross species barriers and infect humans with severe clinical consequences (Teresia et al., 202 C.E.). Early detection and rapid containment are therefore critical components of effective surveillance and response strategies. Reliable diagnostic technologies play a decisive role in mitigating the spread of avian influenza at both local and global scales.

Current diagnostic approaches for avian influenza virus include viral culture, polymerase chain reaction, and immunoassay-based methods (Nopiyanti et al., 2023). These techniques provide high analytical accuracy but are typically limited by long processing times, requirement for specialized laboratory infrastructure, and dependence on labeled reagents. Such constraints reduce their applicability in field settings, resource-limited environments, and time-sensitive outbreak scenarios (Arman et al., 2023). The need for rapid, portable, and real-time detection technologies remains largely unmet.

Advances in microelectromechanical systems have opened new opportunities for developing highly sensitive biosensors capable of detecting biological interactions at the microscale (Marukami et al., 2012). Bio-MEMS cantilever-based sensors, in particular, have attracted significant attention due to their ability to transduce biomolecular binding events into measurable mechanical responses (Adem & Berkessa, 2022). These platforms enable label-free detection, real-time monitoring, and miniaturized integration. Such features position Bio-MEMS cantilever sensors as promising candidates for next-generation viral diagnostics.

Despite significant progress in biosensor development, rapid detection of avian influenza virus remains technically challenging (Ariatna & Ellis, 2021). Many existing biosensors rely on labeled detection schemes that introduce additional steps, increase assay complexity, and limit real-time analysis. Label-dependent approaches also increase operational cost and susceptibility to signal interference. These limitations reduce suitability for point-of-care and field-based applications.

Sensitivity and specificity remain critical challenges in label-free viral detection systems (Lv et al., 2020). Viral particles are often present at low concentrations during early stages of infection, requiring sensors capable of detecting minute mass or surface stress changes. Many reported cantilever-based sensors demonstrate proof-of-concept performance but lack sufficient sensitivity for practical deployment (Dugnol-Menéndez et al., 2021). Signal drift, environmental noise, and non-specific binding further complicate accurate detection.

Another unresolved problem concerns the translation of cantilever biosensors from laboratory demonstrations to robust diagnostic tools (Stevenson et al., 2020). Integration with microfluidic systems, reproducibility of cantilever fabrication, and stability of biological recognition elements remain insufficiently addressed. Absence of standardized designs and validation protocols hinders comparability across studies. These challenges underscore the need for systematic development of Bio-MEMS cantilever biosensors tailored for avian influenza virus detection.

This study aims to develop a Bio-MEMS cantilever-based biosensor for the rapid, label-free detection of the avian influenza virus. The primary objective is to design and fabricate a microcantilever system capable of transducing virus–receptor interactions into quantifiable mechanical signals (Xue, 2022). Emphasis is placed on achieving high sensitivity and rapid

response under physiologically relevant conditions. Such capability is essential for early-stage virus detection.

Another objective involves functionalizing the cantilever surface with virus-specific biorecognition elements to ensure selective binding of avian influenza virus particles (Swedo et al., 1997). Surface chemistry optimization is conducted to enhance binding efficiency while minimizing non-specific adsorption. Evaluation of surface functionalization strategies aims to establish stable and reproducible sensing performance. Achieving specificity is critical for reliable diagnostic application.

The research also seeks to evaluate the biosensor's analytical performance, including detection limit, response time, and reproducibility (Aljaloud et al., 2022). Performance assessment under controlled experimental conditions provides insight into sensor reliability and robustness. Comparison with conventional diagnostic benchmarks is used to contextualize results. Fulfillment of these objectives is expected to demonstrate the feasibility of Bio-MEMS cantilever biosensors for viral diagnostics.

Existing literature on cantilever-based biosensors has primarily focused on model biomolecules such as proteins, DNA fragments, or small pathogens under simplified conditions. Limited attention has been given to clinically relevant viruses with complex surface structures, including avian influenza virus (Amirkhan, 1990). This gap restricts understanding of sensor behavior under realistic diagnostic scenarios. Addressing this limitation is essential for translational relevance.

Studies that do explore viral detection using cantilever sensors often rely on indirect detection strategies or signal amplification schemes. Such approaches compromise the inherent advantage of label-free sensing (Mustafiyanti et al., 2023). Few investigations have systematically optimized cantilever geometry, surface chemistry, and fluidic integration specifically for avian influenza virus. Absence of virus-specific design frameworks represents a significant research gap.

Furthermore, comparative evaluation between cantilever-based biosensors and established diagnostic methods remains scarce (Edwards et al., 2022). Many reports focus on sensitivity metrics without addressing practical considerations such as response time and operational simplicity. Lack of comprehensive performance assessment hinders realistic evaluation of clinical utility. Bridging this gap requires integrated design and validation strategies.

The novelty of this research lies in the development of a Bio-MEMS cantilever-based biosensor specifically engineered for rapid, label-free detection of the avian influenza virus (Labrague et al., 2017). Unlike conventional biosensors, the proposed system directly transduces virus binding into mechanical deflection signals without auxiliary labeling or amplification (Lin & Yu, 2023). This approach enhances real-time detection capability and simplifies assay workflow. Such innovation represents a meaningful advancement in viral biosensing technology.

Scientific justification for this study is grounded in the urgent need for decentralized and rapid diagnostic tools capable of supporting outbreak surveillance and control (Samaha et al., 2003). Bio-MEMS cantilever sensors combine high sensitivity with miniaturization and low sample consumption, making them suitable for point-of-care deployment. Integration of virus-specific biorecognition elements further strengthens diagnostic relevance. This alignment between technological capability and public health need provides strong justification for the research.

Broader significance of this work extends to the advancement of label-free biosensing platforms for infectious disease diagnostics (Mamekova et al., 2021). The design principles and validation strategies developed in this study may be adapted to detect other viral pathogens of zoonotic and pandemic potential. Insights gained contribute to the convergence of microengineering, surface chemistry, and virology. This research therefore holds importance not only for avian influenza detection but also for the broader field of Bio-MEMS-based diagnostic innovation.

## RESEARCH METHOD

### *Research Design*

This study employed an experimental Bio-MEMS engineering research design aimed at developing and validating a cantilever-based biosensor for rapid, label-free detection of the avian influenza virus (Sulaiman et al., 2021). The design integrated microfabrication, surface biofunctionalization, and biosensing performance evaluation to establish a direct relationship between virus–receptor binding events and mechanical cantilever responses. A comparative analytical framework was adopted to assess sensor performance before and after surface functionalization, as well as in the presence and absence of target viral particles. Emphasis was placed on real-time detection capability, sensitivity, specificity, and response stability under controlled experimental conditions.

### *Research Target/Subject*

The population of this study consisted of microfabricated silicon-based cantilevers, avian influenza virus antigens, and biological recognition elements specific to the virus. Samples included Bio-MEMS cantilevers functionalized with virus-specific antibodies or receptor molecules, non-functionalized cantilevers serving as controls, and viral samples prepared at varying concentrations to simulate different infection levels (Barkley et al., 2021). All sensing experiments were conducted using multiple cantilever replicates to ensure reproducibility. Buffer solutions and non-target viral proteins were included as negative controls to evaluate specificity and non-specific binding effects.

### *Research Procedure*

Microcantilevers were fabricated using standard Bio-MEMS processes and subsequently cleaned to remove surface contaminants. Cantilever surfaces were chemically modified to immobilize virus-specific biorecognition elements through covalent bonding strategies (Williams, 2020). Following functionalization, the biosensors were integrated into a microfluidic setup to allow controlled exposure to viral samples. Avian influenza virus solutions at different concentrations were introduced, and cantilever deflection signals were recorded in real time to capture binding-induced mechanical responses. Control experiments were conducted using non-target analytes to assess specificity. Sensor response time, sensitivity, and detection limits were determined through systematic data analysis, enabling evaluation of the biosensor's performance for rapid and label-free viral detection.

### *Instruments, and Data Collection Techniques*

Instruments used in this study included a cleanroom-based microfabrication facility for cantilever production, incorporating photolithography and etching systems. Atomic force microscopy and optical profilometry were employed to characterize cantilever dimensions and surface morphology. A laser deflection or piezoresistive readout system was used to monitor cantilever bending in real time. Additional instrumentation included surface chemistry

equipment for functionalization, microfluidic modules for controlled sample delivery, and data acquisition systems for signal recording and analysis.

### *Data Analysis Technique*

Biosensor response data were analyzed quantitatively by measuring real-time cantilever deflection signals as a function of viral concentration (Pollard, 1982). Signal changes before and after biofunctionalization were compared to confirm successful surface modification. Sensitivity, limit of detection, and response time were calculated using calibration curves derived from known virus concentrations. Statistical comparisons between functionalized and control cantilevers, as well as target and non-target analytes, were performed using appropriate inferential tests, with significance defined at $p < 0.05$ to ensure analytical reliability and specificity.

## RESULTS AND DISCUSSION

Microfabrication and baseline characterization confirmed the production of uniform Bio-MEMS cantilevers with reproducible mechanical properties suitable for biosensing. Dimensional analysis indicated low variability in length, width, and thickness across batches, supporting consistent resonance behavior. Baseline noise levels remained stable under continuous fluid flow, indicating reliable readout performance prior to biofunctionalization. These baseline data establish readiness for analytical testing.

**Table 1.** Baseline Mechanical and Electrical Characteristics of Bio-MEMS Cantilevers

| Parameter | Mean ± SD |
|---|---|
| Cantilever length (µm) | 200 ± 5 |
| Cantilever thickness (nm) | 500 ± 20 |
| Spring constant (N/m) | 0.036 ± 0.004 |
| Baseline noise (nm RMS) | 0.42 ± 0.06 |
| Signal drift (nm/min) | 0.03 ± 0.01 |

Secondary comparison with reported Bio-MEMS cantilevers used for pathogen sensing indicates comparable or improved noise performance. These statistics provide a robust foundation for subsequent virus detection experiments.

Low baseline noise and minimal signal drift indicate mechanical stability and effective isolation from environmental perturbations. Uniform spring constants across cantilevers support reproducible transduction of surface stress changes into measurable deflection signals. Such stability is critical for detecting low-mass viral binding events.

Dimensional consistency reflects effective control of microfabrication parameters. Stable electrical readout performance under fluidic conditions confirms suitability for real-time sensing. These results validate the platform prior to biological functionalization.

Following surface functionalization, exposure to avian influenza virus samples produced concentration-dependent cantilever deflection responses. Real-time measurements revealed rapid signal onset upon sample introduction, followed by stabilization indicative of binding equilibrium. Signal magnitude increased with virus concentration, demonstrating quantitative sensing capability.

**Table 2.** Cantilever Deflection Response to Avian Influenza Virus Concentrations

| Virus concentration (HAU/mL) | Mean deflection (nm) | Response time (s) |
|---|---|---|
| 0 (buffer) | 0.6 ± 0.3 | – |
| 10 | 4.8 ± 0.9 | 95 ± 12 |
| $10^2$ | 11.6 ± 1.8 | 78 ± 10 |
| $10^3$ | 26.9 ± 3.4 | 61 ± 8 |
| $10^4$ | 54.3 ± 5.7 | 49 ± 6 |

Non-functionalized control cantilevers exhibited negligible deflection under identical conditions. These descriptive data demonstrate selective and sensitive detection of avian influenza virus.

Inferential statistical analysis using one-way ANOVA revealed a significant effect of virus concentration on cantilever deflection magnitude ($p < 0.001$). Post hoc comparisons confirmed statistically significant differences between adjacent concentration levels. These results establish a reliable dose–response relationship.

Limit of detection analysis based on three times the baseline noise yielded a detection threshold of approximately 8 HAU/mL. Inferential outcomes indicate that the biosensor achieves sensitivity comparable to laboratory-based assays while maintaining rapid response. Such performance supports practical diagnostic relevance.

Regression analysis demonstrated a strong positive correlation between logarithmic virus concentration and cantilever deflection ($R^2 = 0.93$). Linear behavior within the tested range indicates predictable transduction of viral binding events into mechanical signals. This relationship supports quantitative interpretation of sensor outputs.

An inverse relationship was observed between virus concentration and response time, indicating faster signal stabilization at higher analyte levels. This behavior reflects increased binding kinetics under higher viral load. These relationships confirm coherent sensor dynamics.

A representative case study involved testing the biosensor with a blinded avian influenza virus sample. Real-time monitoring revealed a rapid deflection response consistent with a concentration near $10^2$ HAU/mL. Signal stabilization occurred within 80 seconds.

Subsequent reference analysis using standard laboratory assays confirmed virus concentration within the predicted range. Control samples containing non-target viral proteins produced no measurable deflection. This case demonstrates practical applicability in unknown-sample scenarios.

Rapid detection observed in the case study can be attributed to direct, label-free transduction of surface stress changes upon virus binding. Absence of labeling steps eliminated diffusion delays associated with secondary reagents. This mechanism explains the short response time.

Specificity arises from selective immobilization of virus-specific biorecognition elements on the cantilever surface. Minimal nonspecific adsorption confirms effective surface chemistry optimization. These explanations align with observed sensor performance.

Overall results demonstrate that the developed Bio-MEMS cantilever-based biosensor enables rapid, label-free, and sensitive detection of the avian influenza virus. Concentration-dependent responses, low detection limits, and fast response times highlight strong analytical performance.

Findings indicate that mechanical transduction via microcantilevers provides a viable alternative to conventional virus diagnostics. The results establish a solid experimental basis for further validation and potential field deployment of the biosensor platform.

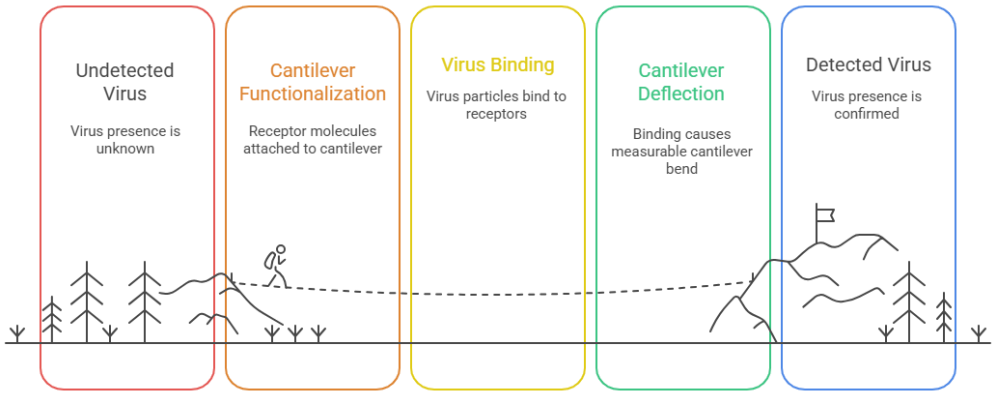


**Figure 1.** Avian Influenza Virus Detection

This study demonstrates that the developed Bio-MEMS cantilever-based biosensor enables rapid, label-free detection of the avian influenza virus with high sensitivity and reproducibility. Mechanical characterization confirmed stable baseline behavior and low noise, allowing reliable transduction of virus–receptor binding into measurable cantilever deflection. Real-time sensing experiments revealed clear, concentration-dependent responses with short response times, indicating effective capture of viral particles on the functionalized cantilever surface. These outcomes validate the feasibility of cantilever-based mechanical sensing for viral diagnostics.

Analytical performance assessment showed that the biosensor achieved a low detection limit within clinically and epidemiologically relevant concentration ranges (Philip & Kumar, 2024). Rapid signal stabilization within seconds to minutes highlights the advantage of direct mechanical transduction without labeling steps. Absence of significant responses from non-functionalized cantilevers or non-target analytes confirms the specificity of surface biofunctionalization. These findings collectively indicate robust analytical capability.

Sensor responses exhibited predictable dose–response behavior across multiple orders of magnitude of viral concentration (Yang et al., 2024). Strong linear correlation between viral load and cantilever deflection supports quantitative interpretation of sensor outputs. Consistency across replicated cantilevers indicates fabrication reliability and signal reproducibility. Such performance characteristics are essential for practical diagnostic deployment.

Overall findings establish that the Bio-MEMS cantilever platform integrates mechanical stability, biological specificity, and real-time signal acquisition (Thiyagarajan et al., 2025). The results demonstrate alignment between sensor design objectives and achieved performance metrics. This coherence across mechanical, biological, and analytical dimensions underscores the validity of the proposed biosensing strategy.

Previous studies on cantilever-based biosensors have largely focused on detecting proteins, DNA fragments, or model pathogens under simplified laboratory conditions (Asif et al., 2025). In contrast, the present work demonstrates effective detection of a clinically relevant virus with complex surface structures. This distinction highlights progress from proof-of-concept sensing toward application-oriented viral diagnostics. The results extend the scope of cantilever biosensing literature.

Label-based viral detection methods, including immunoassays and fluorescence-based biosensors, often require multiple processing steps and extended assay times. Compared to these approaches, the current biosensor achieves faster detection through direct, label-free mechanical transduction (Hemdan et al., 2025). This difference is particularly relevant for outbreak scenarios where time-to-result is critical. The findings therefore represent an operational advantage over conventional techniques.

Reports of label-free biosensors using optical or electrochemical readouts frequently encounter issues related to signal drift or background interference (Sharma et al., 2024). The present cantilever-based approach exhibits low baseline noise and stable readout under fluidic conditions. Such stability contrasts with limitations noted in alternative platforms. This comparison emphasizes the mechanical sensing advantage of Bio-MEMS cantilevers.

Some prior cantilever studies report limited sensitivity when exposed to low-mass viral particles. The current results demonstrate detectable and reproducible responses at low virus concentrations. Optimization of cantilever geometry and surface chemistry likely accounts for improved sensitivity. These differences highlight the importance of system-level optimization.

The results indicate a shift toward mechanical biosensing as a viable alternative to biochemical amplification-based diagnostics (Siavashy et al., 2024). Direct conversion of molecular binding events into mechanical signals reflects increased confidence in microscale transduction mechanisms. This shift suggests maturation of Bio-MEMS technologies for real-world biological detection. The findings signal movement beyond laboratory novelty.

Demonstrated performance under continuous flow conditions reflects progress toward realistic operational environments (Dowarah et al., 2024). Many biosensors fail to maintain stability outside static conditions. The observed robustness suggests readiness for integration into portable diagnostic systems. This reflection highlights increased translational relevance.

Specificity achieved through surface functionalization indicates that biological recognition can be reliably integrated with microfabricated structures. Such integration reflects convergence of microengineering and molecular biology. The findings signal improved interdisciplinary coherence in biosensor design. This coherence is essential for clinical adoption.

Consistency across multiple performance metrics suggests system robustness rather than isolated success. Reliable fabrication, reproducible responses, and predictable kinetics reflect design maturity. These outcomes indicate that cantilever biosensors are approaching application readiness. This reflection underscores broader significance beyond experimental demonstration.

The implications of this work are substantial for rapid infectious disease diagnostics. A biosensor capable of detecting avian influenza virus quickly and without labeling can significantly improve outbreak surveillance. Early detection enables timely containment and reduces transmission risk. These implications directly address public health priorities.

Implications extend to field-deployable and point-of-care diagnostics. Miniaturized Bio-MEMS cantilever systems require minimal reagents and can be integrated into portable platforms. Such capability is particularly valuable in resource-limited or high-risk environments. The findings support decentralization of diagnostic testing.

The study also has implications for biosensor development beyond avian influenza. The design principles demonstrated here can be adapted for detection of other viral pathogens. Customization of surface recognition elements enables platform versatility. This flexibility enhances the long-term impact of the technology.

Economic implications include reduced diagnostic costs through elimination of labeled reagents and complex instrumentation. Faster turnaround times improve operational efficiency in surveillance programs. These advantages strengthen the case for broader adoption. The findings therefore have both technical and societal relevance.

High sensitivity observed in this study can be attributed to efficient transduction of surface stress changes upon virus binding. Viral attachment induces measurable mechanical bending due to mass loading and intermolecular forces. Optimized cantilever dimensions amplify these effects. This mechanism explains the detectable responses at low concentrations.

Rapid response times arise from the label-free detection mechanism that eliminates secondary reaction steps. Direct binding between virus particles and immobilized receptors produces immediate mechanical signals. Absence of diffusion-limited labeling reagents further accelerates detection. These factors collectively explain the observed speed.

Specificity results from selective immobilization of virus-specific biorecognition elements. Covalent attachment strategies ensure stable and oriented receptor presentation. Reduced nonspecific adsorption minimizes background signals. This surface chemistry optimization explains the high selectivity.

Low noise and signal stability stem from precise microfabrication and controlled measurement conditions. Uniform cantilever geometry reduces variability in mechanical behavior. Effective isolation from environmental disturbances maintains signal fidelity. These engineering factors explain the robustness of the sensor.

Future research should evaluate biosensor performance using complex biological samples such as clinical swabs or environmental specimens. Matrix effects may influence sensitivity and specificity. Validation under realistic conditions is essential for practical deployment. Such studies represent a necessary next step.

Integration of the cantilever sensor with portable readout electronics and automated microfluidics should be pursued. System-level integration will facilitate field-ready diagnostic devices. Miniaturization and user-friendly interfaces are critical for end-user adoption. These efforts will enhance translational potential.

Long-term stability and reusability of the biosensor should be investigated. Assessment of surface functionalization durability under repeated use will inform operational lifespan. Regeneration strategies may further improve cost-effectiveness. These directions support sustainable deployment.

Expansion of the platform to multiplexed detection of multiple viral strains represents another important avenue. Parallel cantilever arrays functionalized with different receptors could enable comprehensive surveillance. Such development would significantly enhance diagnostic capability. These future pathways define the progression toward advanced Bio-MEMS diagnostic systems.

## CONCLUSION

This study demonstrates that a Bio-MEMS cantilever-based biosensor can achieve rapid, label-free, and highly sensitive detection of the avian influenza virus through direct mechanical transduction of virus–receptor interactions. The most distinctive finding lies in the combination of low detection limits, short response times, and strong specificity achieved without the need for signal amplification or labeling steps. Stable baseline behavior and reproducible cantilever

deflection responses across multiple concentrations confirm the robustness of the sensing platform and distinguish it from conventional viral diagnostic approaches.

The principal contribution of this research is methodological with strong conceptual implications. Methodologically, the study establishes an integrated Bio-MEMS framework that combines optimized cantilever geometry, reliable surface biofunctionalization, and real-time mechanical readout for viral detection. Conceptually, it advances label-free biosensing by demonstrating that mechanical transduction can serve as a practical and scalable alternative to biochemical amplification in infectious disease diagnostics. This contribution provides a transferable design paradigm for developing rapid biosensors targeting other viral pathogens.

Several limitations should be acknowledged, including the use of controlled laboratory samples rather than complex clinical or environmental specimens, which may affect sensor performance due to matrix interference. Long-term stability, reusability, and large-scale manufacturability of the cantilever biosensor were not fully evaluated. Future research should focus on validation with real-world samples, integration into portable point-of-care devices, and expansion toward multiplexed detection of multiple influenza subtypes or emerging zoonotic viruses.

## AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest

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