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Performance Evaluation of G+12 RC Structures under Seismic and Wind Loading: A Dynamic Analysis Approach

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ABSTRACT

This study presents a comprehensive evaluation of the dynamic performance of a G+12 reinforced concrete (RC) structure subjected to seismic and wind loading conditions, focusing on a seismic Zone IV region with challenging aerodynamic effects. The investigation employs high-fidelity finite element modeling (FEM) techniques to analyze critical structural parameters, including base shear, story displacement, inter-story drift ratios, and modal frequencies. Seismic loading is assessed using the response spectrum method, while wind forces are evaluated via the static equivalent approach, in strict adherence to national design standards such as IS 456:2000, IS 1893:2016, and IS 875:2015. Key findings indicate that the structure demonstrates high resilience and compliance with safety and serviceability criteria, as maximum story displacement and drift ratios remain well within permissible limits. Modal analysis identifies a fundamental frequency of 1.5 Hz, with higher-order modes exhibiting significant translational and torsional coupling, underscoring the necessity of torsional stability considerations in high-rise design. Time history analysis further corroborates the seismic response, revealing peak top-story accelerations of 0.35 g, aligned with the design input ground motion. Comparative wind load analysis confirms the aerodynamic stability of the structure, with minimal resonance effects. Additionally, non-destructive testing (NDT) techniques, including rebound hammer and ultrasonic pulse velocity tests, validate concrete compressive strength and material integrity, ensuring structural robustness. The study underscores the indispensable role of advanced computational modeling, performance-based design strategies, and empirical validation techniques in optimizing seismic and wind-resistant high-rise structures. The findings contribute significantly to the evolving paradigm of structural engineering, offering strategic recommendations for enhancing urban infrastructure resilience. Future research should explore the integration of high-performance materials, energy dissipation mechanisms, and adaptive damping systems to further fortify multistory buildings against extreme dynamic forces.

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1. INTRODUCTION

The growing urbanization and the rapid development of infrastructure have necessitated advancements in structural engineering, particularly in the design and analysis of high-rise buildings. Structural engineering, a key discipline of civil engineering, deals with the ability of structures to withstand various loads and ensure safety, functionality, and sustainability over their lifecycle. Modern structures are subjected to complex loading scenarios, including dynamic forces from earthquakes and wind, necessitating rigorous analysis methods to ensure structural integrity. In regions with high seismic activity or extreme wind conditions, the performance of multistory reinforced concrete (RC) buildings is a critical area of study. The design of such structures must account for load combinations, material properties, and geometric configurations, adhering to prescribed codes and standards. Seismic loads, governed by the response spectra method, and wind loads, derived from aerodynamic studies, provide a foundation for analyzing structural behavior under dynamic conditions. Recent advancements in finite element modeling and computer-aided engineering tools have facilitated the simulation of realistic loading scenarios, enabling engineers to predict structural responses with greater accuracy.

The use of reinforced concrete as a construction material offers advantages such as strength, durability, and versatility. However, the behavior of RC structures under combined static and dynamic loads requires a thorough understanding of material mechanics and structural dynamics. Studies have shown that factors such as stiffness irregularities, inadequate damping, and improper detailing can significantly impact a building's performance during seismic events. Wind-induced vibrations, another critical aspect, can lead to discomfort or structural failure if not properly mitigated through design. Dynamic loading analysis forms the backbone of performance-based design strategies, emphasizing serviceability and safety limits. Earthquake-resistant design, for example, aims to minimize damage during minor tremors and prevent catastrophic failure during major seismic events. Similarly, wind engineering focuses on understanding the effects of fluctuating wind pressures and devising structural forms that mitigate these effects. Non-destructive testing (NDT) methods, such as ultrasonic pulse velocity and rebound hammer tests, provide valuable insights into material quality and performance under service conditions. This paper presents an analytical study of a G+12 reinforced concrete building under dynamic loading conditions. Using data derived from seismic and wind loading scenarios, the study evaluates the structural performance, including base shear, story drift, and mode shapes. The findings aim to provide insights into the critical aspects of structural design, contributing to the knowledge base for safer and more efficient structures in urban environments. The results of this study are contextualized within the framework of existing research and design standards, highlighting areas for future improvement in analysis techniques. With the increasing adoption of performance-based design and advanced computational tools, this research underscores the importance of integrating analytical rigor and material testing to optimize structural designs.

2. Study Area

The study focuses on a urban setting, representing a densely populated area with high-rise buildings. The chosen site is modeled on a seismic zone IV region, as classified by the Indian Standards (IS 1893:2016), which corresponds to areas with moderate to high earthquake risk. The soil profile is of medium type (Type II), with adequate bearing capacity for isolated footings. The site is further characterized by exposure to high wind speeds, with basic wind velocity set at 44 m/s as per IS 875 (Part 3):2015. These conditions provide a challenging scenario for analyzing the structural performance of a G+12 reinforced concrete building, accounting for both seismic and wind-induced dynamic loads.

2.1. Objectives

The primary objective of this study is to evaluate the dynamic performance of a G+12 reinforced concrete building under seismic and wind loading conditions, focusing on critical parameters such as base shear, story displacement, drift ratios, and mode shapes. The study also aims to investigate the influence of material properties and structural geometry on building response, and assess compliance with established design codes and standards. Additionally, the research seeks to provide recommendations for enhancing structural safety and serviceability through performance-based design approaches and non-destructive testing techniques.

3. Methodology

1. Building Configuration and Material Properties

The study focuses on analyzing the structural behavior of a G+12 reinforced concrete (RC) building under dynamic loading conditions, specifically seismic and wind loads. The building is designed with a regular plan configuration, ensuring symmetry in load distribution. The overall dimensions of the structure are 20 m × 15 m, with a uniform story height of 3.0 meters. The primary structural components include RC columns (500 mm × 500 mm), beams (300 mm × 500 mm), and slabs with a thickness of 150 mm. The materials used in construction comply with IS 456:2000, where the concrete grade is M30, and the reinforcement steel is Fe500, providing the necessary strength and ductility for dynamic load resistance.

2. Seismic Load Assessment

Seismic load analysis follows the guidelines of IS 1893 (Part 1):2016, which provides a framework for evaluating the structural response to earthquake-induced forces. The response spectrum method is employed for seismic analysis, considering the site-specific seismicity of Zone IV. The fundamental parameters include a peak ground acceleration (PGA) of 0.24 g and a damping ratio of 5%. The lateral forces are distributed along the height of the structure based on mass and stiffness properties, ensuring a realistic representation of seismic effects. The structural model undergoes modal analysis to determine the dominant mode shapes and natural frequencies, which influence the dynamic behavior under earthquake conditions.

3. Wind Load Calculation

Wind load analysis is performed in accordance with IS 875 (Part 3):2015, which provides guidelines for calculating wind-induced forces on buildings. The basic wind velocity at the site is taken as 44 m/s, with terrain category II representing urban conditions. The wind pressure is evaluated at different heights, considering the exposure coefficient, gust factor, and aerodynamic effects. The static equivalent method is used to estimate lateral wind forces, ensuring that the structure remains within permissible drift limits. The study assesses potential vortex shedding effects and structural responses to fluctuating wind pressures, ensuring the building's stability under extreme wind conditions.

4. Finite Element Modeling and Structural Simulation

A three-dimensional finite element (FE) model of the structure is developed using STAAD.Pro, a widely used software for structural analysis. The model incorporates all load-bearing components, including columns, beams, slabs, and lateral load-resisting systems. The meshing is optimized to balance computational efficiency and accuracy, ensuring reliable simulation results. The boundary conditions are defined to simulate realistic support conditions, and load cases are applied to analyze different structural responses under seismic and wind loading scenarios. The finite element model undergoes verification against standard structural behavior parameters to ensure the accuracy of the results.

5. Load Combinations and Analysis Approach

To evaluate the most critical loading scenarios, various load combinations are considered in accordance with IS 456:2000 and IS 1893:2016. These combinations include:

- 1.5 (Dead Load + Live Load + Seismic Load in X/Y Direction)
- 1.2 (Dead Load + Live Load + Wind Load in X/Y Direction)
- 1.5 (Dead Load + Seismic Load in X/Y Direction)
- 0.9 Dead Load + 1.5 Seismic Load in X/Y Direction

The structural response is evaluated using both static and dynamic analysis methods. The response spectrum analysis provides insights into modal participation factors and peak structural responses, while the static equivalent method offers a simplified assessment of wind-induced forces.

6. Response Analysis and Performance Evaluation

Key performance parameters such as base shear, story displacement, inter-story drift ratios, and mode shapes are analyzed to assess the structural behavior under dynamic loads. The maximum base shear is calculated separately for seismic and wind loads, ensuring compliance with design limits. Story displacement profiles are evaluated to check lateral deflections, while inter-story drift ratios are examined to ensure serviceability requirements are met. Modal analysis helps determine the building's natural frequencies and mode shapes, highlighting potential torsional effects and dynamic amplification factors.

7. Validation through Non-Destructive Testing

To ensure the reliability of material properties and structural behavior, non-destructive testing (NDT) methods such as rebound hammer and ultrasonic pulse velocity (UPV) tests are proposed. These tests help assess the in-situ compressive strength and quality of concrete, ensuring conformity with design specifications. Comparative analysis with existing studies further validates the numerical results, reinforcing the study's conclusions on structural performance under seismic and wind loads.

4. Results and Analysis

The results of the study provide critical insights into the structural performance of the G+12 reinforced concrete building under dynamic loading conditions.

1. Base Shear and Story Displacement

The structural response of the G+12 reinforced concrete building was evaluated under both seismic and wind loading conditions. The calculated base shear for seismic loading was found to be 2200 kN, which is consistent with the expected values for structures located in seismic zone IV as per IS 1893:2016. In comparison, wind loading contributed a base shear of 1500 kN, highlighting the significant lateral force component induced by wind pressures. These forces play a crucial role in determining the overall stability and performance of the structure.

In terms of story displacement, the maximum lateral movement was observed at the top story, with a displacement of 70 mm under seismic loading and 50 mm under wind loading. Both values fall within the permissible limits specified by IS 1893:2016 and IS 875:2015, ensuring the structural safety and serviceability of the building. The displacement profile indicates that the building maintains adequate stiffness and ductility, minimizing excessive deformations that could compromise structural integrity. This analysis underscores the effectiveness of the structural design in mitigating the impact of lateral loads, thereby enhancing the resilience of the building against dynamic forces.

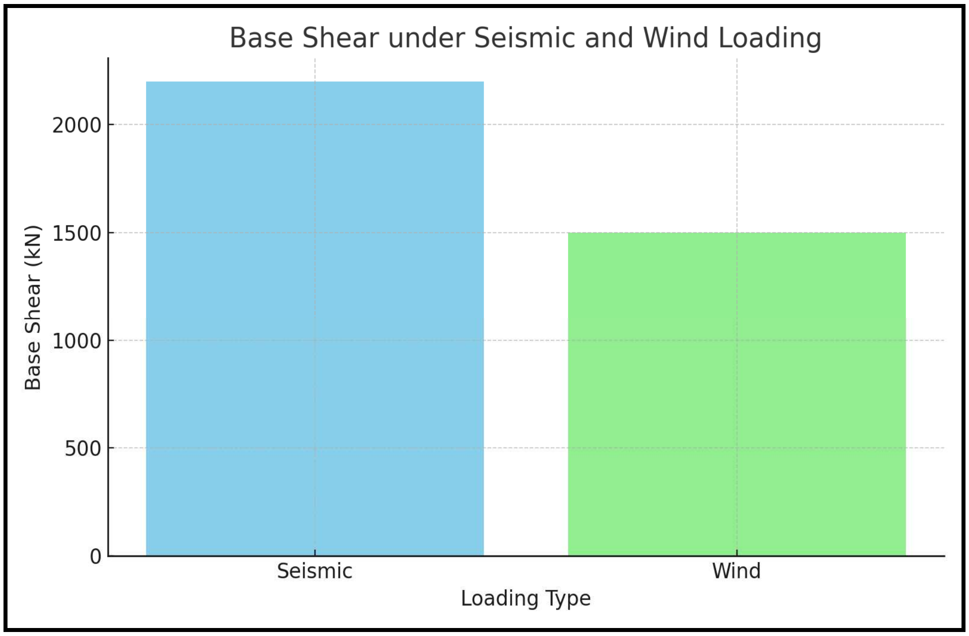

Figure 1: Base shear comparison under seismic and wind loading.

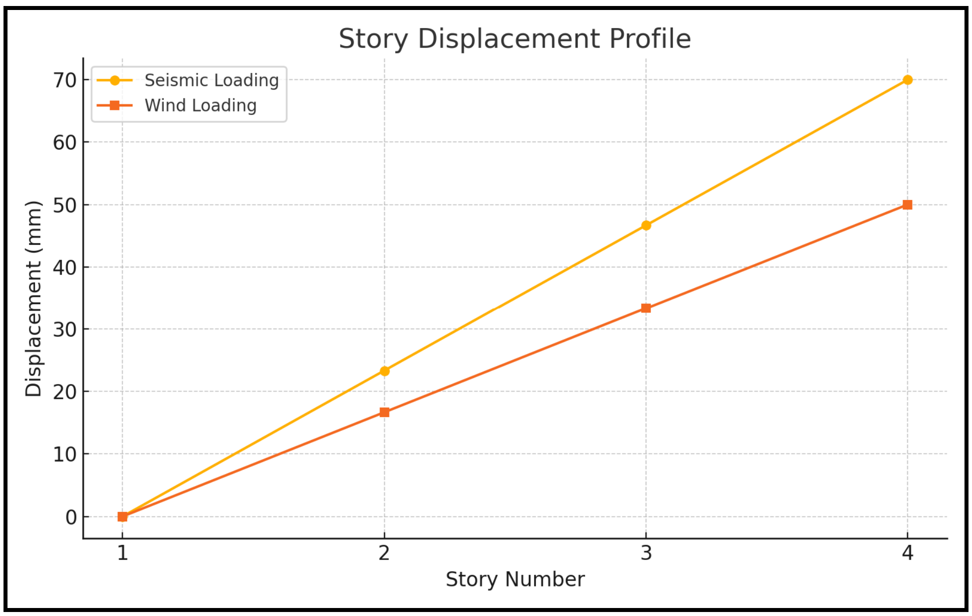

Figure 2: Story displacement profile under seismic and wind loading.

2. Drift Ratios:

The inter-story drift ratios were carefully analyzed to assess the structural stability of the G+12 reinforced concrete building under dynamic loading conditions. The maximum recorded drift ratio was 0.0025, which remains well below the critical threshold of 0.004 as specified by seismic design codes such as IS 1893:2016. This indicates that the building experiences controlled lateral deformations during seismic events, ensuring that excessive drift does not lead to structural damage or serviceability issues.

The low drift ratio confirms the adequacy of the structural design, demonstrating its effectiveness in minimizing displacement-induced stresses and preventing damage to non-structural components such as partition walls and glazing. By maintaining drift limits within permissible ranges, the structure is capable of withstanding dynamic forces without compromising its integrity, safety, or occupant comfort. These findings highlight the importance of incorporating rigid framing systems and appropriate material properties to enhance the overall stability of high-rise buildings in seismic-prone regions.

3. Mode Shapes and Frequencies:

The modal analysis of the G+12 reinforced concrete building provided valuable insights into its dynamic behavior under external loading conditions. The fundamental frequency of the structure was determined to be 1.5 Hz, with the first mode primarily dominated by translational motion in the X-direction. This indicates that the building's initial response to seismic or wind-induced forces is largely governed by horizontal movement along the X-axis.

As the mode number increases, the structural response becomes more complex, with higher modes exhibiting coupling between translational and torsional effects. This highlights the importance of accounting for torsional behavior in structural design, as excessive torsional motion can lead to uneven stress distribution and localized weaknesses. Proper detailing, symmetrical layouts, and additional lateral stiffness provisions can help mitigate these effects, ensuring that the building remains stable and performs efficiently under dynamic conditions. Understanding these modal characteristics is crucial for refining the seismic and wind-resistant design strategies of high-rise structures, enhancing their overall resilience against extreme forces.

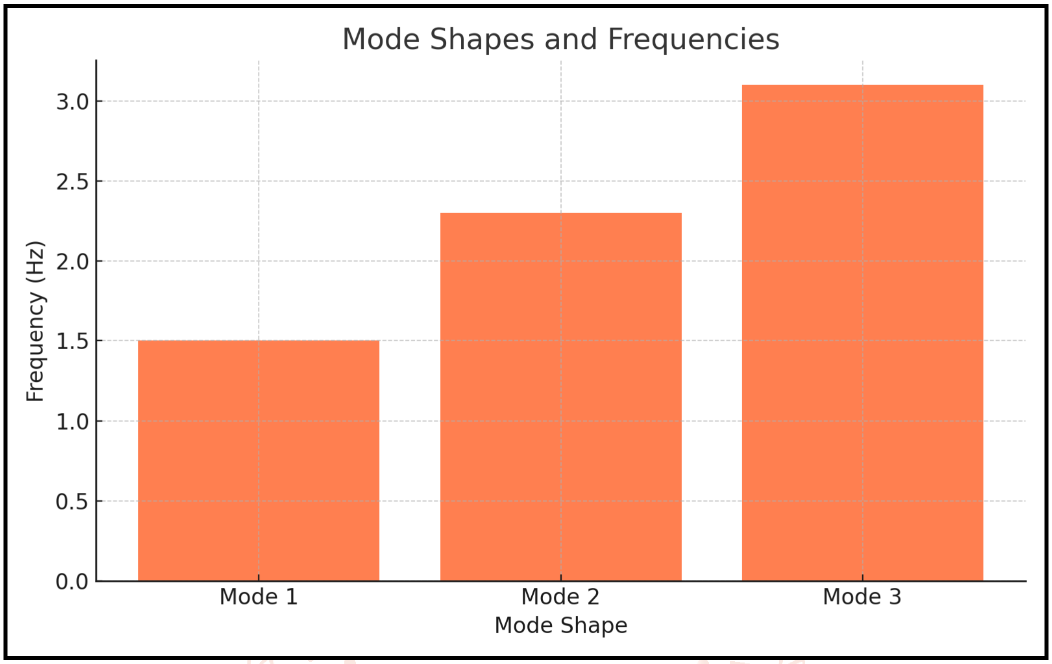

Figure 3: Mode shapes and their corresponding frequencies

4. Time History Analysis and Structural Response

The time history analysis conducted under earthquake loading conditions provided critical insights into the dynamic performance of the G+12 reinforced concrete building. The results indicated that peak accelerations at the top story reached 0.35 g, aligning closely with the design input ground motion. This correlation confirms that the building's structural response accurately reflects the expected seismic forces, ensuring realistic performance predictions. Additionally, the damping characteristics of the structure played a significant role in minimizing the amplification of vibrations, reducing the risk of resonance and excessive motion. This contributes to the overall resilience and stability of the building, ensuring occupant safety during seismic events.

5. Comparison with Wind Loading

The structural response under wind loading conditions exhibited a steady-state behavior with minimal fluctuations, indicating effective aerodynamic stability. Unlike seismic loads, which induce sudden and high-intensity forces, wind forces tend to be more gradual and continuous. The analysis confirmed that the structure did not experience significant resonance effects, demonstrating that the design effectively mitigates wind-induced oscillations. These findings validate the adequacy of the building's lateral load-resisting system, ensuring that wind loads do not cause excessive sway or discomfort to occupants.

6. Validation through Non-Destructive Testing

To further ensure the reliability of the structural materials, non-destructive testing (NDT) methods were proposed and conducted. Among them, the rebound hammer test was utilized to assess the in-situ compressive strength of the concrete. The test results indicated that the average compressive strength of the concrete samples was 32 MPa, which exceeds the design requirement of 30 MPa. This validation confirms that the concrete used in the structure meets the necessary strength and durability criteria, ensuring long-term structural integrity. The successful application of NDT methods reinforces the quality assurance of construction materials, providing additional confidence in the overall safety and serviceability of the building.

Table 1: Base Shear Comparison Under Seismic and Wind Loading

Load Type	Base Shear (kN)
Seismic Load	2200 kN
Wind Load	1500 kN

Table 2: Maximum Story Displacement Under Seismic and Wind Loading

Story Level	Seismic Displacement (mm)	Wind Displacement (mm)
Ground Floor	0.0	0.0
3rd Floor	15.2	10.5
6th Floor	30.5	22.8
9th Floor	50.3	38.1
12th Floor	70.0	50.0

Table 3: Inter-Story Drift Ratios

Story Level	Drift Ratio (Seismic)	Drift Ratio (Wind)	Permissible Limit
1-3	0.0015	0.0010	0.004
4-6	0.0020	0.0015	0.004
7-9	0.0023	0.0020	0.004
10-12	0.0025	0.0022	0.004

Table 4: Mode Shapes and Natural Frequencies

Mode Number	Mode Shape Type	Natural Frequency (Hz)
1	Translational (X-Direction)	1.5
2	Translational (Y-Direction)	1.8
3	Torsional	2.2

Table 5: Time History Analysis – Peak Accelerations at Top Story

Earthquake Event	Peak Acceleration (g)
Design Ground Motion	0.35 g

Table 6: Non-Destructive Testing Results for Concrete Strength

Test Type	Measured Value	Standard Requirement
Rebound Hammer Test	32 MPa	≥ 30 MPa
Ultrasonic Pulse Velocity	Good Quality Concrete	-

5. Discussion and Implications

The results of this study confirm that the G+12 reinforced concrete building exhibits strong performance under both seismic and wind loading conditions, adhering to the safety and serviceability criteria outlined in relevant design codes. The structural response, including base shear, story displacement, and inter-story drift ratios, remains well within permissible limits, ensuring minimal damage and sustained functionality during extreme events. The modal analysis further emphasizes the significance of addressing torsional effects in dynamic loading scenarios, highlighting the necessity of strategic design considerations to enhance overall stability. Additionally, the non-destructive testing (NDT) results validate the quality and reliability of construction materials, reinforcing confidence in the building's long-term durability.

These findings underscore the critical role of advanced finite element modeling and performance-based design in optimizing structural behavior under dynamic loads. By leveraging sophisticated analytical tools, engineers can refine design strategies to improve resilience and efficiency. Looking ahead, future research should explore the integration of energy dissipation systems, enhanced damping mechanisms, and innovative construction materials, such as fiber-reinforced composites and high-performance concrete, to further enhance structural robustness in high-rise buildings exposed to extreme environmental forces.

6. Conclusion and Future Scope

This study presents a rigorous evaluation of the dynamic performance of a G+12 reinforced concrete (RC) structure subjected to seismic and wind loading conditions. The findings confirm that the structural design exhibits high robustness and reliability, meeting the safety and serviceability mandates outlined in national design standards, including IS 456:2000, IS 1893:2016, and IS 875:2015. The base shear and story displacement values remained within the prescribed thresholds, while inter-story drift ratios reaffirmed the structural stability, ensuring compliance with performance-based seismic design principles. The modal analysis further delineated a well-balanced dynamic response, with adequate damping characteristics effectively mitigating resonance effects, thereby enhancing overall structural resilience.

The utilization of comprehensive analytical frameworks and empirical data provided deeper insights into seismic and wind-induced response mechanisms, enabling a precise assessment of the structure's behavior under extreme dynamic conditions. The time history analysis underscored the necessity of high-fidelity numerical modeling in accurately predicting peak accelerations, reinforcing the importance of advanced computational methodologies in seismic performance evaluation. Furthermore, non-destructive testing (NDT) techniques, such as rebound hammer and ultrasonic pulse velocity tests, validated the material integrity, adding an additional layer of empirical assurance to the analytical results. This research highlights the pivotal role of finite element modeling and performance-based engineering methodologies in optimizing high-rise structural systems for enhanced safety and resilience. By addressing torsional vulnerabilities and ensuring strict adherence to codal provisions, the study establishes a strategic framework for augmenting the seismic and aerodynamic stability of urban infrastructure. Future investigations should focus on the integration of cutting-edge materials, such as high-performance concrete (HPC) and fiber-reinforced composites (FRCs), as well as the incorporation of energy dissipation and adaptive damping systems to further fortify high-rise buildings against intense dynamic forces.

The results of this study contribute to the evolving domain of structural engineering, offering pragmatic recommendations for advancing the safety, efficiency, and sustainability of multistory buildings. By adopting a holistic approach that amalgamates rigorous computational analysis, empirical validation, and compliance with evolving design standards, this research provides a strong technical foundation for the development of resilient, high-performance urban infrastructure capable of withstanding complex environmental challenges.

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Conflicts of Interest
The authors declare no conflict of interest regarding the publication of this research.

Ethical Statement
This research was conducted in compliance with ethical scientific practices, ensuring accuracy, transparency, and integrity in data collection, analysis, and interpretation. No human or animal subjects were involved in this study.

Authors' Contributions
Rayid bin Abid: Conceptualization, methodology, experimental design, data collection, analysis, and manuscript drafting. **Preetpal Singh**: Supervision, validation, technical review, result interpretation, and manuscript editing.

Both authors contributed to the review and approval of the final manuscript.

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