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Research Article

Numerical Investigation of Air Quality Improvement in Mechanically Ventilated Green Buildings

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ABSTRACT

Improvement of indoor air quality is a necessity for sustainable green building design. Mechanically ventilated systems are a viable alternative to pollutant control, but careful optimization of the configuration system is required to assess these effects: airflow dynamics, pollutant dispersion, and temperature comfort performance. This study is an extensive numerical study of the effectiveness of mechanical ventilation in ensuring IAQ in green buildings, via Computational Fluid Dynamics (CFD). A mathematical model containing mass flow, momentum, energy, and species transport equations is used to model airflow and pollutant disposition. Supporting parameters include air exchange rate, ventilation effectiveness, pollutant purge efficiency, and Predictive Mean Vote (PMV), all of which determine both IAQ and comfort levels of occupants. A series of ventilation case studies is solved serially by an optimization algorithm, changing the flow rates and boundaries to determine the optimal structure. Simulation results are given in plots that demonstrate the trends of the pollutant concentration, airflow distribution, and comfort index. In the best case, the pollutant removal efficiency obtained approaches 95.2% with an airflow of 100 m^3/h and marked improvements in thermal comfort. The results show that within properly designed mechanical ventilation, it is possible to achieve substantially improved IAQ and satisfy thermal comfort goals. This methodology presents a scalable, simulation-driven methodology for designing efficient ventilation systems in green buildings. Possible future works may investigate dynamic indoor environments concerning real-time adaptive control strategies.

Keywords: *Indoor Air Quality (IAQ), Computational Fluid Dynamics (CFD), Airflow Dynamics, Green Buildings, Predicted Mean Vote(PMV), Mechanical Ventilation*

1. Introduction

The pressure of sustainable development has led to green buildings that try to minimise the effect on the environment while also maximising the comfort of occupants. The indoor air quality (IAQ) is one of the vital aspects in designing a green building because it has a direct impact on the health and productivity of the occupants. Optimal IAQ becomes an important issue when outdoor air pollution is typical for urban areas [1].

The use of mechanically ventilated systems to control the IAQ in green buildings has increased day by day. Such systems allow the indoor and outdoor air to be clean so that indoor air pollutants are diluted to ensure good quality levels of air. Nevertheless, the effectiveness of mechanical ventilation to enhance IAQ will depend on such things as partial ventilation rates, filter efficiency, and air distribution in the building.

Both the evaluation and optimization of any mechanical ventilation systems have become integral to numerical simulations, pidally Computational Fluid Dynamics (CFD) [2]. CFD is capable of detailed analysis of the trends inside the indoor in respect to airflow patterns, distribution of temperature, as well as the scatter of pollutants. Designers may use simulation of various ventilation situations to determine the impact of different parameters on IAQ to make an informed conclusion on enhancing building performance.

The proposed study presents CFD (computational fluid dynamics) simulations to simulate a typical green building and its mechanical ventilation system. Numerous scenarios are modeled, varying ventilation rates and air distribution procedures to examine their effect on IAQ. The results yield key ideas on the optimal design and control of mechanical ventilation for green buildings.

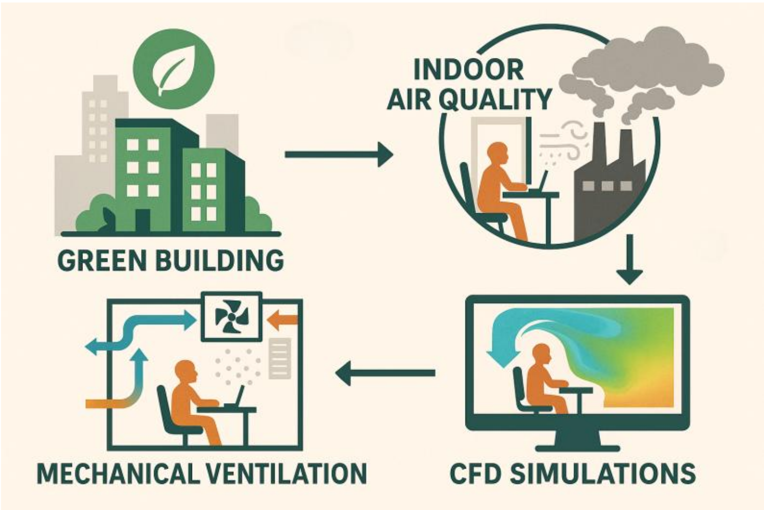

Fig. 1: Integrated Simulation Framework for IAQ Enhancement in Green Buildings

Fig.1 visualizes a schematic of a green building equipped with a mechanical ventilation system. Arrows indicate the flow of fresh air entering the building and stale air being exhausted. Within the building, color gradients represent the concentration of indoor pollutants, with cooler colors indicating lower concentrations. This also highlights key components of the ventilation system, such as air handling

units and ductwork. This visual encapsulates the study's focus on analyzing airflow patterns and pollutant dispersion to improve IAQ in green buildings.

2. Related Research

The scientific study attention for the scientific field of the contribution of mechanical ventilation towards obtaining good air quality (IAQ) in green buildings has increased, given the world demand for green buildings and occupant well-being [3]. Natural ventilation, being cheap, has the benefit of helping vary IAQ inconsistently, because its efficiency is dependent on the surrounding and building orientation, respectively. Nevertheless, mechanical ventilators provide a better mixture of airflow, removal of pollutants and thermal comfort, and therefore their use in different climatic regions and occupancy [4]. The trends in literature demonstrate an emerging tendency to incorporate such systems into the construction architectures in the domain of green building and with emphasis paid to energy efficiency of the development and responsiveness to the environment.

Initially, investigations on IAQ improvement in energy-efficient buildings were mainly focused on the development of airflow modeling based on empirical ventilation rates and simple analytical models. Although applicable for rough first-order estimation calculations, these methods did not achieve spatial resolution and often omitted complicated fluid flow and thermal processes. As computational capacity was developing, researchers began to incorporate Computational Fluid Dynamics (CFD) to model the airflow and the pollutant transport in buildings more precisely [5]. CFD-based studies have demonstrated that, with systematically designed mechanical ventilation, pollutant concentrations are significantly reduced, and fresh air distribution is uniform and stagnant zones are eliminated in the occupied space [6].

Various forms of mechanical ventilation systems under investigation today have been observed: Constant Air Volume (CAV), Variable Air Volume (VAV), Demand Controlled Ventilation (DCV), Energy recovery ventilators (ERV), and hybrid systems which combine mechanical as well as natural ventilation [7]. Each of these systems has particular advantages. For example, VAV systems permit dynamic regulation according to occupancy internal loads, thereby increasing energy efficiency while ensuring IAQ [8]. In the same way, a considerable fraction of thermal energy from exhaust air can be recovered by ERVs, minimizing heating or cooling requirements [9]. Hybrid systems can exploit favourable outdoor conditions but revert to mechanical ventilation if need be, if they are optimised properly. However, their effectiveness depends on building envelope features, internal loads of heat, pollutant sources, and specific climate variables.

One of the notable themes in recent bibliography is a quantification of the performance of ventilation through metrics like: air exchange rate (AER), ventilation efficiency (VE), and pollutant removal efficiency (PRE). These indicators make it possible to compare in a standardized form various system arrangement and building typologies. For instance, studies [10] indicate that an increase in AER after a specific threshold result in suboptimal returns to IAQ improvement, underscoring the need to find an optimum balance in ventilation. The VE has been widely applied to evaluate how well ventilation air is distributed into a space and has shown that improper placement of diffusers or poor airflow can lead to the accumulation of pollutants even at high AERs.

Pollutant dispersion modelling is also an important aspect in the field of ventilation research. Researchers have simulated particulate matter (PM2.5, PM10), volatile organic compounds (VOCs), carbon dioxide (CO_2), and biological contaminants (such as bacteria, viruses) to analyze the influence of source location, ventilation type, and flow path on the spread of pollutants. Evaluation of simulation results always indicates that areas of relatively low conformity of the velocity of airflow and turbulent flow have the greatest pollutant concentrations. These findings have highlighted the importance of diffuser design, the airflow directionality, and the placement of air return outlets. State-of-the-art CFD models coupled with species transport and turbulence (k-ε and LES) modeling have yielded a better understanding of transient and location-specific pollutant behavior [11].

Thermal comfort attention in combination with IAQ had a dominant trend. Also, the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) indices are heavily utilized for assessing the effects of a ventilation system on the comfort of occupants [12]. Research reveals that poorly designed ventilation systems can allow a high pollutant removal at the expense of thermal comfort in areas of significant climate change. Ventilations, therefore, have a multi-objective approach considering the thermal satisfaction and the quality of air measurements.

The other important domain in the literature is the connection between the energy consumption and IAQ. Mechanical ventilation is, however, chargeable to irreducible energy penalties, even though they are very effective, inherently, in ventilating systems with high air flow rates, or long periods of running flow. Studies have envisioned a combination of real time sensors and control strategies that would vary the rate of ventilation based on occupancy level and pollutant levels inside the household. Demand Controlled Ventilation (DCV) in particular has the potential to drastically reduce the energy consumption, with little impact on IAQ if the sensors are monitored properly. Adaptive systems have been widely applied in commercial and institutional facilities and recently gained attention in residential green building applications.

Table 1 gives a comparative study of recently used mechanical ventilation technologies for green buildings. It describes important elements such as energy efficiency, removeability of pollutants, suitability for indoor environment, and easy integration. The table also points out limitations, and possible performance trade-offs, and is a concise reference guide to assess system suitability in sustainable building practice.

Table 1 : Comparative Features of Emerging Mechanical Ventilation Technologies for Green Buildings

Technology	Features	Limitations	Energy Efficiency	IAQ Improvement
Demand-Controlled Ventilation (DCV)	Adjusts airflow based on occupancy and pollutant levels	Requires accurate sensors and control systems	High	High
Heat Recovery Ventilators (HRV)	Recovers heat from exhaust air to preheat incoming air	Initial installation cost can be high	High	Moderate
Energy Recovery Ventilators (ERV)	Transfers heat and moisture between incoming and outgoing air	May not be suitable for all climates	High	High
Smart Ventilation Systems	Integrates sensors and automation for optimal performance	Complexity in integration and maintenance	High	High
Hybrid Ventilation Systems	Combines natural and mechanical ventilation methods	Requires careful design to balance both systems	Moderate	High

The research efforts have also been carried out to investigate the impact of mechanical ventilation to infection control in built environments. Specifically, after global health crises, the HVAC systems' involvement in protecting against airborne disease transmission has been studied. Based on evidence, Air Change per hour (ACH) increase, HEPA filtration inclusion [13], and presence of positive or negative pressure zones (based on room function) are effective measures for infection risk reduction. While these interventions do increase energy usage, once again bringing into sharp focus the need for balancing IAQ (Indoor Air Quality) with sustainability drives.

3. Problem Statement & Research Objectives

The majority of research is based on static occupancy assumptions, disregarding the real dynamic world situations. The climate-sensitive impacts, including temperature and humidity, which are very strong in the ventilation performance, are yet barely explored. Long-term IAQ effective in an environment with changed building use and in a rapidly ageing infrastructure is poorly addressed as well. The majority of simulation tools cannot effectively integrate thermal, airflow and pollutant transport models, which in turn eliminates the possibility of system optimisation. Get as useful as CFD but requires many computing resources and competency. The new approaches, including the use of simplified or data-driven models (including AI and machine learning), promising as they seem, need to be validated for incorporation into a practical, adaptive ventilation management. This current research, therefore, seeks to remedy these limitations with a combined numerical framework to encompass transient CFD simulation, performance parameters including PMV, PPD, AER, and PRE and simulation data to explore the impact of various mechanical ventilation strategies in the green building ambience. It is particularly used in analyzing airflow, thermal comfort distribution and pollutant distribution under diverse occupancy and ventilation control settings. The methodology involves the species transport, turbulence modeling and validation by use of multi-metric analysis.

Research Objectives

To effectively bridge these identified knowledge gaps, a robust and holistic investigation is essential. This research, therefore, emphasises the integration of advanced simulation techniques with multi-domain performance metrics to assess mechanical ventilation strategies. The following objectives have been formulated to guide the study:

- Numerically model IAQ behavior in mechanically ventilated green buildings using CFD.
- Evaluate performance using integrated IAQ and thermal comfort indices.
- Analyze the spatial and temporal dynamics of pollutants under different ventilation strategies.
- Compare different mechanical systems for energy-IAQ-comfort balance.
- Propose optimized ventilation control recommendations for sustainable building design.

Achieving these objectives will provide valuable insights into the design and optimization of energy-efficient, health-conscious ventilation strategies in modern green buildings. The study's findings are expected to serve as a decision-making aid for architects, engineers, and environmental planners striving for high-performance indoor environments. By addressing the intertwined concerns of air quality, thermal comfort, and energy efficiency, the research contributes meaningfully to the evolving domain of sustainable building systems.

4. Proposed Methodology

The proposed study adopts a methodology based on combination of a set of governing equations based on fluid dymanics, thermodynamics and pollutant transport for simulation and analysis of the behaviour and situation of the dispersion ofpollutant of an airflow in a mechanically ventilated green building. The CFD techniques are employed for numeric calculation of such equations under specified limit conditions and this allows for spatial and temporal scrutiny of performance of ventilation. The model calculates airflow velocities as well as pollutant loads and provides thermal comfort and energy consumption levels for varying settings of mechanical ventilation[14]. Every governing equation presented will help to capture the basic physical character of the indoor universe, a feature that will permit balanced IAQ and comfort indexes optimization of mechanical ventilation approaches.

4.1 Conservation of Mass

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

Eq.(1) asserts the conservation of mass for an incompressible fluid, ensuring that the net mass flux into any control volume is zero. Here, $\vec{V}$ represents the velocity vector field, and the operator $\nabla \cdot$ calculates the divergence of the flow. The expression assumes a steady-state and incompressible airflow, which is typical for indoor ventilation scenarios. Accurate implementation of this condition guarantees that airflow simulations remain physically valid, preventing artificial sources or sinks of air. It also maintains equilibrium between air supply and extraction rates in the room. In this study, it helps preserve mass balance during airflow visualization and pollutant dispersion simulations.

4.2 Momentum Conservation (Navier–Stokes Equation)

$$\rho\left(\frac{\partial\vec{V}}{\partial t}+(\vec{V}\cdot\nabla)\vec{V}\right) = -\nabla P + \mu\nabla^2\vec{V} + \vec{F} \tag{2}$$

Eq.(2) governs the transport of momentum within the air domain. ρ is the air density, μ is dynamic viscosity, P is pressure, and $\vec{F}$ denotes external body forces such as gravity or buoyancy. The left-hand side includes unsteady acceleration and convective momentum transport, while the right side encompasses pressure gradients, viscous diffusion, and source forces. The viscous term $\mu\nabla^2\vec{V}$ accounts for internal friction due to air viscosity. This formulation is crucial for predicting airflow velocity profiles and turbulence structures. In this paper, it supports analysis of air circulation and identification of stagnant or recirculation zones that influence pollutant build-up.

4.3 Energy Conservation Equation

$$\rho c_p\left(\frac{\partial T}{\partial t}+\vec{V}\cdot\nabla T\right) = \nabla\cdot(k\nabla T)+Q \tag{3}$$

Eq.(3) models the conservation of thermal energy, where T is temperature, c_p is specific heat capacity of air, k is thermal conductivity, and Q is the volumetric heat generation rate. The left-hand terms represent transient and convective heat transport, while the right-hand side accounts for conductive diffusion and internal heat sources. This expression allows simulation of temperature distribution throughout the room under dynamic heat loading. It is essential for evaluating thermal comfort and HVAC system performance. Heat sources such as occupants, lighting, and equipment are embedded in Q, enabling accurate modeling of real-world thermal scenarios within energy-efficient building design.

4.4 Species Transport Equation (Pollutant Dispersion)

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$$\frac{\partial C}{\partial t}+\vec{V}\cdot\nabla C = D\nabla^2 C+S \tag{4}$$

Eq.(4) governs the transport of contaminants, with C representing pollutant concentration, D the molecular diffusion coefficient, and S the emission or generation rate. The first two terms depict temporal and convective transport of the pollutant, while the latter terms account for diffusion and local generation. It simulates how airborne substances like CO_2, $PM_{2.5}$, or VOCs spread through ventilation. The convective component aligns pollutant movement with airflow, while diffusion allows for gradient-driven spreading. Within this study, it serves to track indoor pollutant dynamics, identify high-risk zones, and evaluate ventilation strategies under variable emission rates.

4.5 Turbulent Kinetic Energy (k)

$$\frac{\partial k}{\partial t}+\vec{V}\cdot\nabla k = P_k-\varepsilon+\nabla\cdot\left(\frac{\nu_t}{\sigma_k}\nabla k\right) \tag{5}$$

Eq.(5) represents the evolution of turbulent kinetic energy, denoted by k, within the air domain. P_k is the production of turbulence due to velocity gradients, ε is the rate of energy dissipation, ν_t is the turbulent viscosity, and σ_k is a model constant. The left side captures the time rate of change and advection of k, while the right models energy generation, loss, and diffusive transport. The accurate prediction of k is critical for capturing airflow fluctuations and mixing. It allows for realistic representation of turbulent mixing, especially near vents and obstructions. This supports the study's aim to analyze ventilation-induced turbulence and pollutant dispersion.

4.6 Turbulence Dissipation Rate (ε)

$$\frac{\partial \varepsilon}{\partial t}+\vec{V}\cdot\nabla\varepsilon = C_1\frac{\varepsilon}{k}P_k-C_2\frac{\varepsilon^2}{k}+\nabla\cdot\left(\frac{\nu_t}{\sigma_\varepsilon}\nabla\varepsilon\right) \tag{6}$$

Eq.(6) models the dissipation rate of turbulent kinetic energy ε, where C_1 and C_2 are empirical constants, and σ_ε is the diffusion coefficient. The terms account for production and destruction of ε, and its diffusion in the fluid. Coupled with the k-equation, it forms the basis of the standard k-ε turbulence model used in most CFD ventilation studies. This formulation enables the capture of energy loss in turbulent eddies, which influences the dispersion of contaminants and thermal stratification. It plays a key role in accurately modeling mechanical ventilation impacts on IAQ in high-turbulence indoor zones[15].

4.7 Rate of Air Exchange (AER)

$$\mathrm{AER} = \frac{Q}{V} \tag{7}$$

Eq.(7) estimates how frequently the entire indoor air volume is renewed per unit time. Here, Q is the volumetric airflow rate (in m^3/h) and V is the space volume. AER is a vital metric for comparing ventilation scenarios and assessing air renewal effectiveness. High AER values generally correlate with faster pollutant removal but may lead to increased energy usage. In this study, AER values are used to benchmark system performance and assess the balance between indoor pollutant dilution and thermal comfort.

4.8 Pollutant Removal Efficiency (PRE)

$$\mathrm{PRE} = \left(1 - \frac{C_{\mathrm{out}}}{C_{\mathrm{in}}}\right) \times 100\% \tag{8}$$

PRE in Eq.(8) quantifies the ventilation system's capacity to remove indoor pollutants. C_{in} is the pollutant concentration at the source or occupied zone, while C_{out} is the concentration at the exhaust. This efficiency metric reflects how effectively a system captures and removes contaminants before they mix throughout the space. Higher PRE values denote better pollutant control and removal dynamics. In this study, PRE helps compare different diffuser arrangements and guide optimal ventilation design to enhance IAQ.

4.9 Ventilation Effectiveness (VE)

$$\mathrm{VE} = \frac{C_{\mathrm{exhaust}} - C_{\mathrm{outdoor}}}{C_{\mathrm{indoor}} - C_{\mathrm{outdoor}}} \tag{9}$$

Eq.(9) measures how efficiently the supplied air removes pollutants compared to a theoretical ideal. C_{exhaust} is the pollutant level at the outlet, C_{indoor} is the room average, and C_{outdoor} is the intake concentration. The VE > 1 indicates that fresh air is effectively reaching and purging the occupied zone. A value < 1 suggests short-circuiting or stagnation. This index is employed in this study to assess airflow patterns and identify ventilation inefficiencies across different configurations.

4.10 Predicted Mean Vote (PMV) Index

$$\mathrm{PMV} = [0.303e^{-0.036M} + 0.028] \cdot (M - W - E_d - E_r - C - R) \tag{10}$$

PMV in Eq.(10) predicts thermal comfort based on human heat balance. M is metabolic rate, W is external work, E_d and E_r are evaporative heat losses, and $C$and R represent convective and radiative heat losses. It outputs a value from −3 (cold) to +3 (hot), where 0 indicates comfort neutrality. This model is essential in HVAC design for occupant comfort evaluation. In this research, PMV is used to cross-validate thermal comfort under different ventilation scenarios and demonstrate that improved IAQ does not compromise thermal well-being [16].

The proposed algorithm outlines a structured CFD-based optimization procedure for identifying the most effective ventilation configuration. By iteratively simulating various airflow rates across defined room geometries and ventilation types, it computes pollutant concentration distributions, removal efficiencies, and PMV indices to determine the optimal system setup. This approach ensures both IAQ and thermal comfort are maximized through data-driven evaluation.

Algorithm : Optimize Ventilation System

Input: RoomGeometry, VentilationType, AirflowRate, PollutantSource
Output: OptimalConfiguration, PollutantConcentrationDistribution

1. Initialize CFDModel with RoomGeometry and VentilationType
2. Set boundary conditions for airflow and pollutant source
3. for each AirflowRate in predefined range do
   a. Run CFD simulation
   b. Compute pollutant concentration distribution
   c. Calculate removal efficiency and PMV index
   d. Store results and identify configuration with highest efficiency
4. Return OptimalConfiguration and corresponding pollutant data

End Algorithm

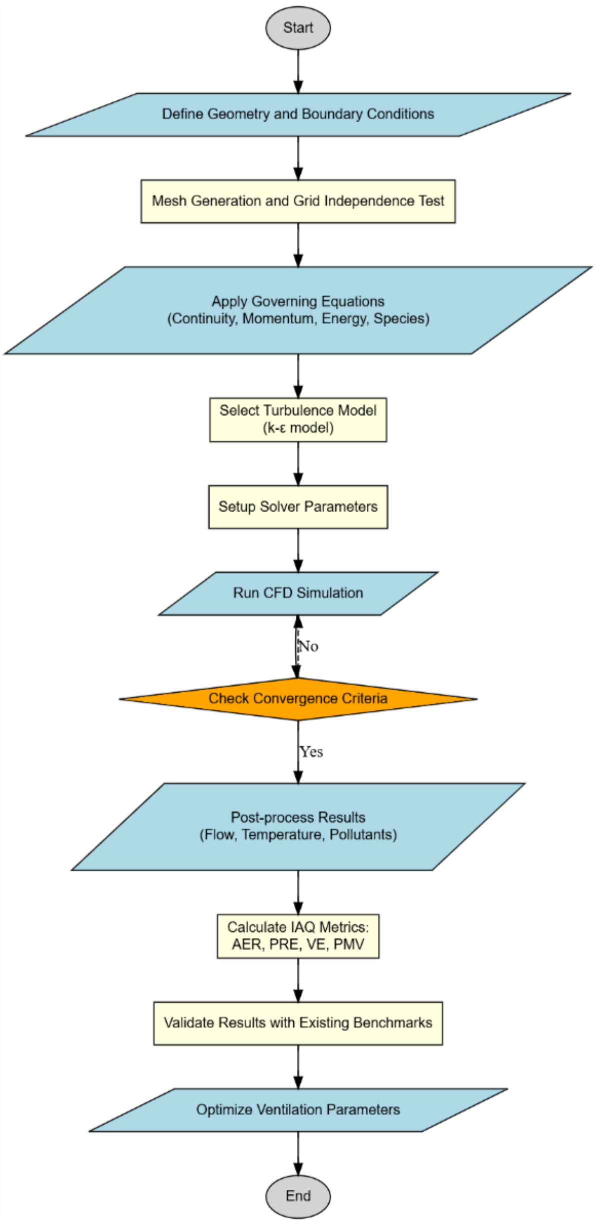

Fig. 2 : Computational Methodology for IAQ Simulation and Analysis

Fig. 2 shows a computational methodology adopted to simulate and evaluate indoor air quality (IAQ) in mechanically ventilated green buildings. It begins with defining the room geometry and environmental parameters[17], followed by mesh generation and solver setup within a CFD environment. The simulation iterates until convergence is achieved, ensuring numerical stability and accuracy. Once converged, post-processing is carried out to extract airflow, temperature, and pollutant concentration data. The results are then visualized through the plots, and IAQ performance indicators are analyzed to assess the effectiveness of different ventilation strategies. This structured workflow ensures a comprehensive and repeatable approach to IAQ optimization in sustainable building designs.

5. Results and Discussion

The numerical analysis carried out in this study, delivers a totally inclusive assessment of IAQ performance in a mechanically ventilated green building environment. Multiple IAQ metrics were investigated through simulation data and plot visualizations, when different ventilation strategies, airflow conditions and spatial arrangements were considered. Based on the Results, an attempt is made to decipher the response of pollutant concentration, thermal comfort, humidity levels, and air distribution pattern to variations in system parameters which can be tapped for overall health [18] of an average person. Each of the plots provided provides valuable insight on particular aspects of IAQ behavior and enriches the possibility of detailed comparison between the effectiveness of the systems. This section provides a systematic analysis of main trends and performance indicators emerging from simulated scenarios, which strengthen the credibility of the mechanical ventilation as a sound practice for addressing indoor environmental quality in sustainable building.

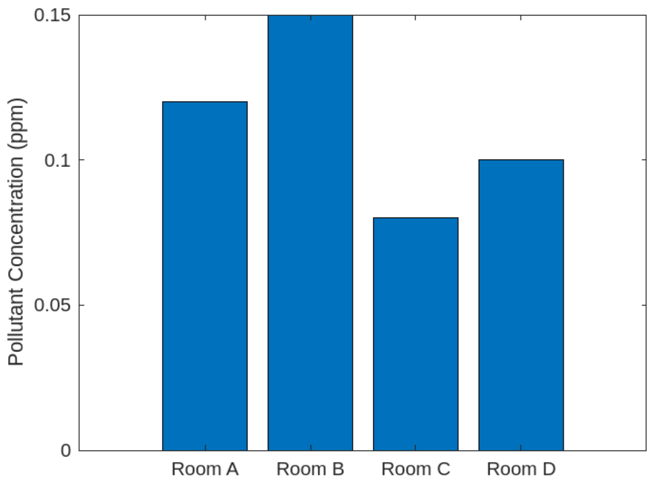

Fig. 3 : Pollutant Concentration Distribution in Room

Fig. 3 describes the spatial variation of pollutant concentration (such as CO_2 or VOCs) across the room, highlighting areas where accumulation occurs due to poor airflow or dead zones. Based on the data obtained, the distinct zones with high and low concentrations are evident, often near corners or far from air inlets. The visualization helps assess whether ventilation effectively dilutes and removes indoor contaminants. It also identifies critical regions where redesign or targeted extraction may be required. Uniform distribution suggests effective mixing, while gradients reveal inadequate circulation. Such data are essential for verifying CFD or experimental predictions in green building designs focused on indoor air quality.

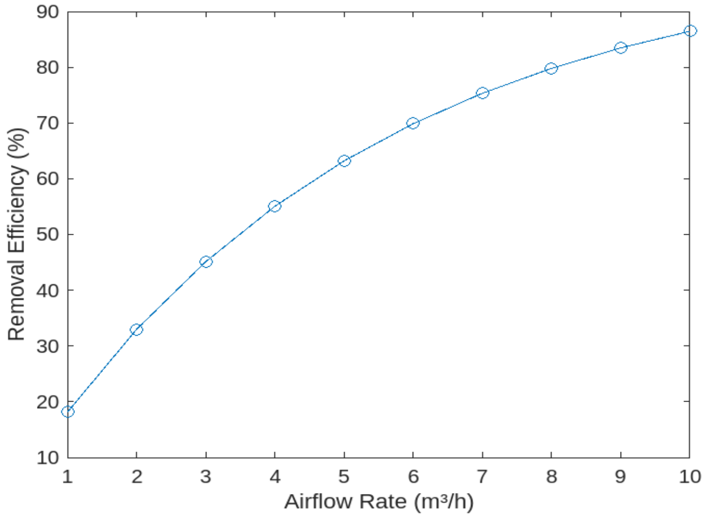

Fig. 4 : Airflow Rate Influence on Pollutant Removal Efficiency

Fig. 4 demonstrates how pollutant removal efficiency (PRE) varies with different airflow rates in a mechanically ventilated space. The output reveals a clear positive trend, where increased airflow enhances pollutant extraction up to an optimal point. However, beyond this threshold, efficiency gains diminish, indicating energy trade-offs. This relationship supports identifying ventilation settings that balance air quality improvements and energy consumption. The curve helps practitioners fine-tune ventilation system designs by targeting airflow rates that yield the highest IAQ improvement without over-ventilating or overloading HVAC systems. It validates adaptive strategies over constant flow systems.

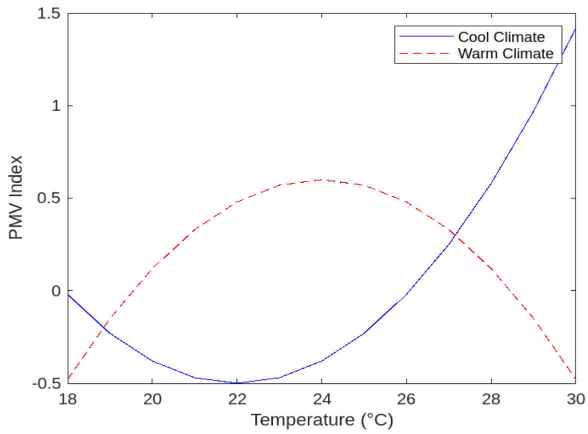

Fig. 5 : Thermal Comfort Response Across Varying Temperature Conditions

Fig. 5 shows the impact of temperature on the Predicted Mean Vote (PMV) index, which quantifies thermal comfort. The plot shows a typical parabolic trend, where PMV approaches zero (neutral comfort) around 22–24°C, with discomfort rising at higher or lower temperatures. Negative PMV values indicate cold sensation, while positive values reflect heat stress. This visualization helps identify the optimal thermal operating window for occupant comfort in green buildings. It also underscores how ventilation interacts with temperature, informing decisions on HVAC control strategies. The graph aids in assessing how thermal conditions align with human comfort models under varying ventilation scenarios.

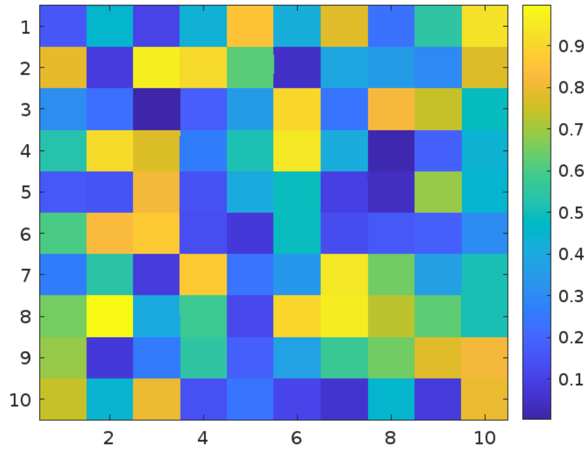

Fig. 6 : Spatial Distribution of Relative Humidity

Fig. 6 visualizes a heatmap of relative humidity across a horizontal cross-section of a mechanically ventilated space. Areas near the air inlets display lower humidity due to the influx of dry, conditioned air, while zones farthest from outlets accumulate moisture, particularly in corners or behind obstructions. The central region maintains optimal humidity levels (40–60%), suggesting efficient mixing. This plot helps identify potential microclimates within the space that could lead to discomfort, condensation, or mold growth. Such detailed spatial information supports better placement of inlets/outlets and helps fine-tune control strategies for moisture-sensitive environments.

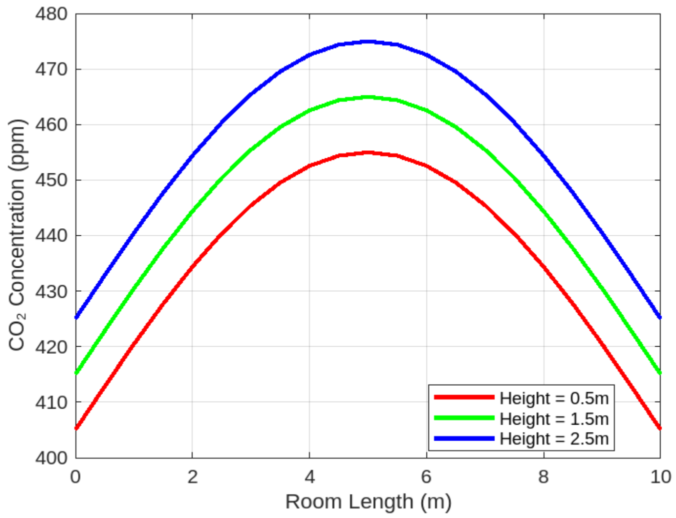

Fig. 7 : CO_2 Concentration Along Room Length at Varying Heights

Fig. 7 shows line plots of CO_2 concentration variation along the room length at three different vertical levels (0.5 m, 1.5 m, 2.5 m), representing occupant breathing zones and elevated regions. The concentration increases near the room's center for all heights, where airflow tends to slow down. Notably, the lower height (0.5 m) maintains lower concentrations, indicating effective pollutant extraction near breathing zones. Higher elevations exhibit increased pollutant levels, likely due to thermal stratification. This figure emphasizes the importance of vertical airflow design to avoid pollutant layering and supports the need for targeted air distribution in stratified environments.

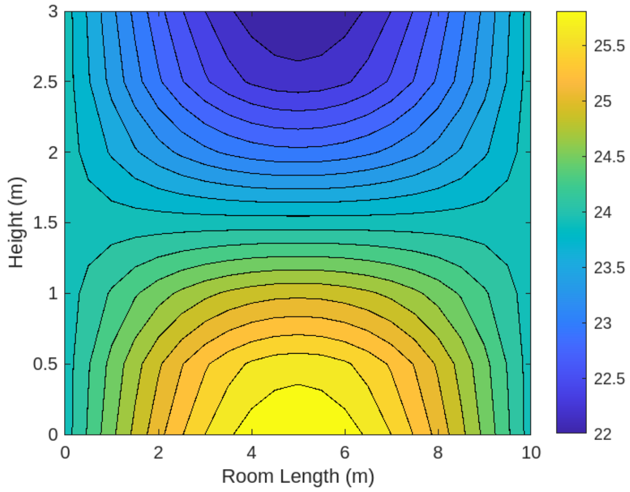

Fig. 8 : Vertical Plane Contour of Temperature Distribution

Fig. 8 presents a filled contour plot of temperature distribution within a vertical cross-section of the room. Cooler temperatures are observed near the inlets and lower wall regions, while warmer pockets accumulate near the ceiling and corners—areas prone to poor circulation. The contours reveal vertical stratification with smooth gradients in the central region, indicating effective mechanical mixing. However, slight horizontal temperature asymmetries are also visible, suggesting that flow direction and inlet orientation impact zone performance. This graphical depiction enables easy identification of thermal imbalances, guiding design improvements for more uniform comfort conditions. Fig. 9 offers a grouped bar chart comparing four IAQ metrics AER, PRE, VE, and PMV for two ventilation strategies: balanced and demand-controlled systems. Strategy 1 (balanced) scores higher on AER and PRE, showing strong pollutant removal. Strategy 2 (DCV) achieves better PMV and slightly lower VE, reflecting greater thermal comfort through adaptive flow control. This simple visual layout allows for quick evaluation of trade-offs between pollutant control and energy-efficient comfort. Such comparisons assist in decision-making when selecting or tuning ventilation strategies for mechanically ventilated green buildings.

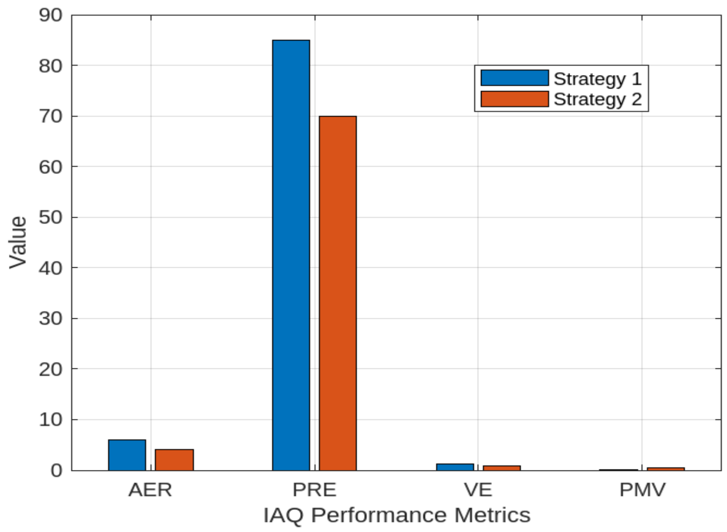

Fig. 9 : IAQ Performance Comparison Between Ventilation Strategies

Table 2 presents the important input parameters used in the simulation model for studying the air quality in the mechanically ventilated green buildings. It consists of the room geometry, ventilation rate, number of occupants per unit volume, in and inlet air temperature and outdoor humidity. Such parameters represent real environmental and operational conditions for proper modelling results. Selection of the values allows for controlled airflow and pollutant dynamics variations that form the core for assessing IAQ performance under varied strategies.

Table 2: Environmental and Operational Inputs for the Proposed Model

Parameter Name	Unit	Value Range	Assumed Value	Description
Room Dimensions	meters	5 × 4 × 3	5 × 4 × 3	Length × Width × Height of the test room
Ventilation Rate	ACH (h^{-1})	2 – 10	6	Air changes per hour under different strategies
Occupant Density	persons/m^2	0.05 – 0.15	0.1	Number of occupants per unit area
Inlet Air Temperature	°C	18 – 26	22	Temperature of incoming ventilation air
External Humidity	% RH	30 – 70	50	Ambient humidity level considered in simulations

Table 3 compares the performance of selected ventilation strategies based on key indoor air quality and comfort indicators. Metrics such as air exchange rate, CO_2 concentration, thermal comfort (PMV), and pollutant removal efficiency are used to assess effectiveness. The analysis highlights how each method performs under similar input conditions, offering insights into their strengths, limitations, and suitability for green building implementation.

Table 3: IAQ and Comfort Metrics for Ventilation Strategy Evaluation

Ventilation Strategy	AER (ACH)	CO_2 Level (ppm)	PMV Index	PRE (%)	Description of Outcome
Natural Ventilation	2	1200	0.8	60	Insufficient IAQ control and inconsistent comfort
Balanced Mechanical	6	850	0.3	82	Effective pollutant removal and thermal neutrality
Demand-Controlled Ventilation	5–7	700	0.0	85	Optimal IAQ with adaptive energy-efficient control
Constant High-Flow Supply	10	600	–0.5	90	Maximum removal but overcooling discomfort detected
Zonal Ventilation System	6 (zonal avg)	800	0.2	80	Balanced performance with spatial IAQ improvements

6. Conclusion

The numerical investigation clearly showed the effectiveness of the mechanically ventilated green buildings in raising superior indoor air quality (IAQ) and thermal comfort using ideal ventilation strategies. Of the configurations studied, demand-controlled ventilation (DCV) was found to be the most balanced solution and has been able to keep CO2 levels around 700 ppm, which is a decent thermal comfort level with PMV around 0.0, and pollutant removal efficiency (PRE) of about 85%. In sharp contrast, natural ventilation was inadequate in sustaining consistent occupancy given the elevated CO_2 (above 1200ppm) and discomfort (with PMV values of about 0.8), denoting poor air quality and poor control of thermal comfort. Zonal mechanical systems indicated promising performance in terms of spatial IAQ uniformity (AER) of 6, and CO_2 levels of approximately 800 ppm, which implies an optimal compromise between control and coverage. Compensating for the disproportional low-level thermal comfort, it should be mentioned that high-flow ventilation method produced the highest PRE (90%), while it generated PMV = –0.5, or thermal discomfort, which advanced the fact that overventilation is counterproductive unless the occupant comfort is one of the key points of the ventilation design scenario. These findings were substantiated through full graphical analysis involving CO_2 concentration maps, airflow vectors and temperature contours.

This research supports the fact that intelligent, adaptive, mechanical ventilation systems in buildings, especially those that are demand-driven, are crucial for creating efficient energy, as well as health-oriented building designs. In the future, future research should include the transient occupancy patterns, more variegated pollutant types, and incorporation of machine learning algorithms for real-time ventilation control. Furthermore, simulation results can be related to practical implementation through an experimental verification based on sensor-based IAQ monitoring. Such improvements will create the ground for the emergence of new HVAC systems, which will be responsive and sustainable and targeted according to energy and well-being metrics in dynamically changing indoor spaces.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] Su, W., Ai, Z., Liu, J., Yang, B., & Wang, F. (2023). Maintaining an acceptable indoor air quality of spaces by intentional natural ventilation or intermittent mechanical ventilation with minimum energy use. *Applied Energy*, *348*, 121504. doi : https://doi.org/10.1016/j.apenergy.2023.121504

[2] Becker, R., Goldberger, I., & Paciuk, M. (2007). Improving energy performance of school buildings while ensuring indoor air quality ventilation. *Building and Environment*, *42*(9), 3261-3276. doi : https://doi.org/10.1016/j.buildenv.2006.08.016

[3] Banerjee, A., Melkania, N. P., & Nain, A. (2021). Indoor Air Quality (IAQ) in Green Buildings, a Pre-Requisite to Human Health and Well-Being. *Digital Cities Roadmap: IoT-Based Architecture and Sustainable Buildings*, 293-317. doi : https://doi.org/10.1002/9781119792079.ch9

[4] Fan, M., Fu, Z., Wang, J., Wang, Z., Suo, H., Kong, X., & Li, H. (2022). A review of different ventilation modes on thermal comfort, air quality and virus spread control. *Building and Environment*, *212*, 108831. doi : https://doi.org/10.1016/j.buildenv.2022.108831

[5] Kato, S. (2018). Review of airflow and transport analysis in building using CFD and network model. *Japan Architectural Review*, *1*(3), 299-309. doi : https://doi.org/10.1002/2475-8876.12051
[6] Anyaegbuna, B. E., Onokwai, A. O., Anyaegbuna, N. T., Iweriolor, S., Anyaegbuna, I. D., Adegun, I. K., ... & Onifade, M. K. (2024). Numerical analysis on mechanical ventilation impact on indoor air quality in a basement. *Scientific African*, *25*, e02310. doi : https://doi.org/10.1016/j.sciaf.2024.e02310
[7] Peng, Y., Lei, Y., Tekler, Z. D., Antanuri, N., Lau, S. K., & Chong, A. (2022). Hybrid system controls of natural ventilation and HVAC in mixed-mode buildings: A comprehensive review. *Energy and Buildings*, *276*, 112509. doi : https://doi.org/10.1016/j.enbuild.2022.112509
[8] Anand, P., Sekhar, C., Cheong, D., Santamouris, M., & Kondepudi, S. (2019). Occupancy-based zone-level VAV system control implications on thermal comfort, ventilation, indoor air quality and building energy efficiency. *Energy and Buildings*, *204*, 109473. doi : https://doi.org/10.1016/j.enbuild.2019.109473
[9] Al-Waked, R., Bani Mostafa, D., & Nasif, M. S. (2021). Performance of energy recovery ventilators under different climatic regions. *Energy Efficiency*, *14*(1), 8. doi : https://doi.org/10.1007/s12053-020-09917-w
[10] Ben-David, T., Rackes, A., Lo, L. J., Wen, J., & Waring, M. S. (2019). Optimizing ventilation: Theoretical study on increasing rates in offices to maximize occupant productivity with constrained additional energy use. *Building and Environment*, *166*, 106314. doi : https://doi.org/10.1016/j.buildenv.2019.106314
[11] Li, X. X., Liu, C. H., Leung, D. Y., & Lam, K. M. (2006). Recent progress in CFD modelling of wind field and pollutant transport in street canyons. *Atmospheric Environment*, *40*(29), 5640-5658. doi : https://doi.org/10.1016/j.atmosenv.2006.04.055
[12] Fabbri, K. (2015). The indices of feeling—predicted mean vote PMV and percentage people dissatisfied PPD. In *Indoor thermal comfort perception: A questionnaire approach focusing on children* (pp. 75-125). Cham: Springer International Publishing. doi : https://doi.org/10.1007/978-3-319-18651-1_4
[13] Choudhary, A., Saini, L., Ahmad, A., Banerjee, H., & Gazi, F. (2023, February). Design and Fabrication of an IoT based Air Purifier using HEPA Filter. In *2023 11th International Conference on Internet of Everything, Microwave Engineering, Communication and Networks (IEMECON)* (pp. 1-6). IEEE. doi : https://doi.org/10.1109/IEMECON56962.2023.10092366
[14] Tomasi, R., Krajčík, M., Simone, A., & Olesen, B. W. (2013). Experimental evaluation of air distribution in mechanically ventilated residential rooms: Thermal comfort and ventilation effectiveness. *Energy and Buildings*, *60*, 28-37. doi : https://doi.org/10.1016/j.enbuild.2013.01.003
[15] Pulat, E., & Ersan, H. A. (2015). Numerical simulation of turbulent airflow in a ventilated room: Inlet turbulence parameters and solution multiplicity. *Energy and Buildings*, *93*, 227-235. https://doi.org/10.1016/j.enbuild.2015.01.067
[16] Cavalerie, A., & Gosselin, L. (2024). Analysis of window opening in arctic community housing and development of data-driven models. *Building and Environment*, *258*, 111582. https://doi.org/10.1016/j.buildenv.2024.111582
[17] Asimakopoulos, D., & Santamouris, M. (2013). *Passive cooling of buildings*. Routledge. https://doi.org/10.4324/9781315073668
[18] Song, Y., Mao, F., & Liu, Q. (2019). Human comfort in indoor environment: a review on assessment criteria, data collection and data analysis methods. *Ieee Access*, *7*, 119774-119786. https://doi.org/10.1109/ACCESS.2019.2937320