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Identifying the Optimal Plant-to-Room Volume Ratio for Enhancing Indoor AQI in Naturally Ventilated Bangalore Homes

Harshan J[1], Prof. Aleena M S[2], Prof. Ashik S[3], Dr Shilpa Madangopal[4]

[1]*Student, School of Architecture, CHRIST (Deemed to be University), Bengaluru*
[2]*Professor*, School of Architecture, CHRIST (Deemed to be University), Bengaluru

[3]*Assistant Professoi, School of Architecture, CHRIST (Deemed to be University), Bengaluru -*

ashik.s@christuniversity.in

[4]*Professor, School of Architecture, CHRIST (Deemed to be University), Bengaluru -*

shilpa.madangopal@christuniversity.in

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1. INTRODUCTION

1.1 Background of the Study

Quality of the air indoors has gotten progressively more important in the context of built spaces because it affects human health, cognitive performance, comfort level and well-being directly. People spend around 80–90% of their time indoors in modern urban lifestyles — specifically, at home. Consequently, indoor air quality has become an essential factor in sustainable architectural design.

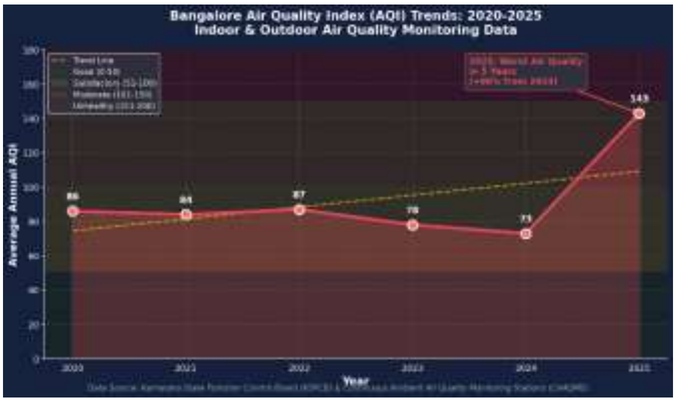
Indoor environments are composed of a complex mixture of internal and external sources of pollutants. Particles such as carbon dioxide (CO2), particulate matter (PM2. 5) and volatile organic compounds (VOCs). These contaminations are formed due to occupant breathing, building materials and furniture, cleaning agents, cooking activities, and outdoor air leakage. Consequences of long-term exposure to high indoor pollutant concentrations can be observed in respiratory diseases, allergic reactions and decreased physical performance as well as cognitive performance with chronic health consequences.

Air change rate (ACH) and MERV filters are invaluable to maintaining indoor air quality, but both require extensive mechanical ventilation systems. Natural ventilation through operable windows is still the main mode of air exchange, but this works only in large residential buildings — particularly in Indian urban contexts. Although natural ventilation reduces indoor CO2 generated by human activity, it also allows outdoor particulate pollutants to enter. So, passive and idle energy supplementary strategies needed to improve the indoor air quality stability.

An increasing number of homes are incorporating indoor plants as part of the biophilic design principles. In addition to their aesthetic and psychological benefits, plants are often promoted as natural air purifiers. Despite laboratory studies demonstrating the possibility of pollutant absorption under controlled conditions, there are still no quantitative guidelines outlining how plant density should be scaled in relation to room volume in realistic residential settings.

This study closes that gap by investigating the optimal plant-to-room volume ratio required to attain measurable improvements in indoor air quality under naturally ventilated conditions in Bangalore.

1.2 Context of the Research



1.2.1 Geographical Context: Bangalore's Urban Environment

Bangalore reflects an urbanized metropolitan environment with compact residential apartments, natural ventilation, increasing levels of outdoor pollution, and an emphasis on passive methods for indoor environmental control. The moderate climate in Bangalore facilitates natural ventilation in buildings, minimizing the need for mechanical HVAC systems. However, with increasing urbanization and traffic pollution levels are high in Bangalore.

The residential buildings in Bangalore are not isolated from environmental influences. Pollutants are able to penetrate into the indoor environment through windows and ventilating openings. This provides a dynamic interaction between the outdoor and indoor environment. In compact residential apartments in Bangalore, bedrooms can vary in area from 8 to 12 m².

1.2.2 Climatic Context: Natural Ventilation Dynamics

Bangalore's moderate climate supports frequent window-based ventilation. Windows are typically partially opened—approximately 20–30%—to balance airflow with privacy, rain protection, and dust control. This partial opening results in moderate air change rates, creating a controlled but limited ventilation environment.

Natural ventilation is a passive airflow system driven by pressure differentials created by wind forces and thermal buoyancy. Unlike mechanical ventilation, natural ventilation is not constant; it fluctuates with climatic conditions and occupant behavior. In practice, residential windows are rarely fully open, making partial opening representative of realistic usage patterns.

1.2.3 Architectural Context: Compact Residential Typologies

Urban housing trends increasingly favor compact rooms due to high land costs and vertical development. Smaller rooms exhibit faster pollutant accumulation due to reduced air volume. In a 9m² room with 3m ceiling height (27m³ total volume), pollutant concentration can increase rapidly if ventilation is insufficient.

This makes room volume a critical variable in IAQ modeling and justifies the use of plant-to-room volume ratio rather than simple plant count as the primary metric for environmental design.

1.3 Rationale and Need for the Study

Despite widespread belief that indoor plants improve air quality, there is no clear, evidence-based guideline defining the number of plants required per unit room volume to achieve measurable improvement in indoor air quality under naturally ventilated residential conditions in Bangalore.

Existing research predominantly focuses on laboratory chamber experiments, mechanically ventilated commercial spaces, and species-specific pollutant absorption. There remains a gap in field-based residential studies, density-based scaling frameworks, and context-specific evaluation under natural ventilation.

The concern for indoor environmental quality gained prominence during the late twentieth century with the identification of "Sick Building Syndrome" in tightly sealed commercial buildings. In developing countries such as India, IAQ concerns are intensified by high ambient pollution levels. Urban cities frequently experience elevated particulate concentrations due to vehicular emissions, construction activity, and industrial discharge.

Simultaneously, there has been a growing cultural and architectural interest in incorporating indoor plants within residential interiors. While this trend aligns with sustainable and biophilic design philosophies, its environmental performance remains insufficiently quantified in real-world conditions.

Therefore, the background of this study lies at the intersection of urban indoor air quality challenges, natural ventilation dynamics, biophilic architectural integration, and the need for measurable design guidelines.

1.4 Research Problem Statement

There is a systematic disconnect between laboratory-based phytoremediation research and real-world residential application. While sealed chamber studies demonstrate significant pollutant removal by plants, these conditions eliminate ventilation effects, use artificially elevated pollutant concentrations, and employ plant-to-volume ratios that are unrealistically high for residential spaces.

In naturally ventilated environments, ventilation rate often dominates pollutant dynamics, potentially overwhelming the observable effect of plant-based removal mechanisms. Without standardized ventilation conditions and volume-normalized density metrics, results cannot be meaningfully compared across different spatial scales.

This research seeks to address whether increasing plant-to-room volume ratio produces measurable reduction in CO2, PM2.5, and VOC levels under natural ventilation, and at what density the rate of improvement begins to plateau.

1.5 Aim and Objectives

The aim of this study is to identify the optimal plant-to-room volume ratio for enhancing indoor air quality in naturally ventilated residential rooms in Bangalore.

The objectives of this research are: (1) To measure baseline indoor air quality parameters (CO2, PM2.5, and VOCs) in selected naturally ventilated residential rooms; (2) To introduce incremental plant density levels while maintaining constant ventilation and occupancy conditions; (3) To analyze the variation in indoor air quality across different plant-to-room volume ratios; (4) To identify threshold behavior and diminishing returns in plant density effectiveness; and (5) To propose a practical, evidence-based guideline for integrating indoor plants in residential architecture.

1.6 Research Questions

The study is guided by analytical research questions: Does increasing plant density produce measurable reduction in CO2, PM2.5, and VOC levels under natural ventilation? How does plant-to-room volume ratio influence pollutant stabilization trends? At what density does the rate of improvement begin to plateau? Can an optimal density range be derived that balances environmental effectiveness and spatial efficiency? How can this density guideline be integrated into practical residential design strategies in Bangalore?

1.7 Scope and Limitations

The scope defines the boundaries within which the research is conducted. The spatial scope includes residential rooms located within Bangalore urban region, compact rooms approximately 9m² in area, and naturally ventilated typology without mechanical HVAC. The environmental scope encompasses measurement of three primary pollutants (CO2, PM2.5, and VOCs), controlled ventilation maintained at 25% window opening, and single-occupant monitoring.

The analytical scope includes quantitative comparison across defined plant density phases, percentage reduction calculation, and identification of optimal density threshold. Exclusions comprise commercial or institutional buildings, cross-ventilation comparative studies, long-term seasonal monitoring, advanced statistical modeling, and psychological perception or user-experience studies.

Limitations include limited sample size focusing on a single room configuration, short monitoring duration where pollutant stabilization trends may differ over extended periods, external AQI influence from fluctuating outdoor pollution levels, species-specific performance not isolated as the study focuses on density rather than individual species, and absence of advanced statistical modeling as regression analysis was beyond the scope.

1.8 Significance and Expected Contribution

The significance of this research extends beyond the immediate objective of identifying an optimal plant-to-room volume ratio. It contributes to environmental design discourse, sustainable architecture practice, and indoor environmental research within the Indian context.

The environmental significance lies in providing measurable evidence of pollutant stabilization through plant density, evaluating plant effectiveness under realistic ventilation conditions rather than laboratory chambers, and demonstrating threshold behavior in environmental systems. Rather than treating indoor plants as symbolic green elements, the study quantifies their environmental role.

The architectural significance involves introducing plant-to-room volume ratio as a quantifiable planning metric, linking environmental performance with spatial design decisions, and encouraging architects to incorporate vegetation at the conceptual design stage. By proposing a clear density range (plants per cubic meter), the study provides a design tool applicable in interior layout planning, residential design guidelines, and sustainable building certification.

The sustainability significance demonstrates that plant density optimization can enhance indoor environmental performance without mechanical intervention. Although plants do not replace ventilation systems, they reduce pollutant concentration incrementally and improve overall environmental stability. In climates like Bangalore's—where natural ventilation is widely practiced—plant-based IAQ enhancement can function as a supplementary sustainability strategy.

The regional significance addresses Bangalore's specific conditions: residential apartments are compact, natural ventilation is common, outdoor pollution levels are rising, and indoor environmental control relies primarily on passive strategies. By providing a density guideline suited to small bedrooms (approximately 9m²), the study addresses real spatial conditions rather than theoretical models.

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2. LITERATURE REVIEW

2.1 Conceptual Foundations

The study is built upon three primary conceptual domains: Indoor Air Quality Theory, Natural Ventilation Dynamics, and Biophilic Design and Phytoremediation. These domains form an integrated environmental system within residential architecture.

2.1.1 Indoor Air Quality Theory

Indoor Air Quality refers to the chemical, physical, and biological conditions of indoor air that affect occupant health, comfort, productivity, and well-being. IAQ is typically evaluated through measurable parameters such as carbon dioxide, particulate matter, volatile organic compounds, relative humidity, and temperature.

Indoor air behaves as a dynamic equilibrium system where pollutant concentration reflects the balance between generation (G), ventilation (Q), and removal (R). This relationship is expressed in the steady-state mass balance equation: $C = G/(Q+R)$, where C is pollutant concentration, G is generation rate, Q is ventilation rate, and R is removal rate.

This theoretical model highlights why plant density must be examined relative to ventilation rate. Increasing plant biomass increases R, but if Q dominates the system, the observable effect of R may be limited.

Carbon dioxide concentration is widely used as an indicator of ventilation adequacy. However, plant-mediated CO2 removal is biologically constrained as photosynthesis depends on light intensity, leaf area, duration of exposure, and plant metabolic state. Under typical indoor lighting, photosynthetic rates are relatively low, making significant CO2 reduction through plants alone unlikely in ventilated spaces.

Particulate matter behaves differently from gaseous pollutants. PM2.5 concentration indoors is influenced by outdoor air quality, infiltration rate, indoor activities, surface deposition, and resuspension. Plants may reduce PM through physical deposition on leaf surfaces, with efficiency depending on leaf texture, surface roughness, air velocity, and spatial distribution.

Volatile Organic Compounds are chemically reactive pollutants emitted from indoor materials. Plant-based VOC reduction occurs through stomatal absorption, cuticular uptake, and rhizosphere microbial degradation. The soil-root interface significantly contributes to VOC breakdown, implying that removal capacity is linked to both leaf biomass and soil volume.

2.1.2 Natural Ventilation Dynamics

Natural ventilation is a passive airflow system driven by pressure differentials created by wind forces and thermal buoyancy. Key parameters influencing natural ventilation include window opening percentage, building orientation, wind speed and direction, temperature gradients, room geometry, and obstructions within space.

Unlike mechanical ventilation, natural ventilation is not constant; it fluctuates with climatic conditions and occupant behavior. Partial opening (approximately 20–30%) represents realistic usage patterns influenced by privacy concerns, rain ingress, noise, and dust infiltration.

Ventilation performs a dual role: dilution mechanism for indoor-generated pollutants and infiltration pathway for outdoor contaminants. In cities with moderate to high outdoor pollution levels, ventilation may improve CO2 while increasing particulate load, creating a complex environmental balance.

2.1.3 Biophilic Design and Phytoremediation

Biophilic design theory proposes that humans possess an innate connection to natural systems. However, the environmental performance of plants must be examined beyond psychological benefits.

Early experimental studies conducted in controlled chambers demonstrated significant pollutant removal by certain plant species. These studies suggested that plants could act as natural air purifiers. However, subsequent critiques identified limitations: sealed conditions eliminate ventilation effects, pollutant concentrations are often artificially elevated, plant density relative to chamber volume is unrealistically high, and air mixing is uniform unlike real buildings.

Field-based studies generally report moderate reductions in VOC concentration, minor to modest reduction in CO2 levels, and limited impact on PM2.5 under high ventilation conditions. Unlike sealed chambers, ventilated spaces introduce air exchange, which often dominates pollutant behavior.

2.2 Theoretical Models and Standards

The mass balance model assumes that indoor pollutant concentration reaches equilibrium when the rate of pollutant generation equals the combined rate of removal and ventilation exchange. This model is significant because it quantifies pollutant dynamics, identifies ventilation as a dominant control factor in naturally ventilated buildings, and introduces removal mechanisms as a potential supplementary pathway.

Environmental systems often demonstrate nonlinear behavior. As plant density increases, removal capacity increases initially; however, beyond a threshold, additional plants may produce marginal improvements due to airflow saturation, reduced effective air contact, and ventilation dominance. This concept of diminishing returns forms the theoretical basis for the research hypothesis.

Health-based standards provide benchmarks for evaluating environmental quality. The World Health Organization (WHO) Indoor Air Quality Guidelines define recommended exposure limits based on epidemiological research. The Central Pollution Control Board (CPCB) AQI Standards categorize air quality based on pollutant concentration ranges including Good, Satisfactory, Moderate, Poor, Very Poor, and Severe categories.

2.3 Review of Empirical Studies

Global research on plant-based air purification can be broadly categorized into controlled chamber experiments and field-based building studies. Laboratory studies report substantial pollutant reduction, particularly for

VOCs, with reductions of significant percentages within controlled timeframes. However, methodological limitations include sealed conditions, absence of ventilation, artificially elevated pollutant concentrations, unrealistically high plant-to-volume ratios, and short monitoring durations.

Field studies in offices and classrooms generally report moderate reductions in VOC concentration, minor to modest reduction in CO2 levels, and limited impact on PM2.5 under high ventilation conditions. Several studies observe threshold behavior, where increasing plant quantity beyond a moderate level produced diminishing returns.

Indian empirical research on indoor air quality primarily emphasizes pollutant measurement and exposure assessment rather than intervention-based studies. Studies in urban Indian cities report elevated indoor PM2.5 due to outdoor infiltration, seasonal variation in particulate concentration, high VOC presence in newly constructed buildings, and CO2 accumulation in densely occupied spaces.

2.4 Identification of Research Gaps

The literature review reveals significant gaps: over-reliance on laboratory-based studies that eliminate ventilation effects; limited residential context studies as most field research focuses on offices and educational institutions; absence of standardized plant-to-room volume ratios as few studies normalize plant quantity to room volume; limited exploration of threshold and diminishing returns behavior; inadequate ventilation control in field studies; insufficient Indian urban context validation; disconnect between environmental theory and architectural practice; limited multi-parameter analysis; and lack of small-room focus as urban housing trends favor compact rooms.

2.5 Conceptual Framework

The conceptual framework integrates three core systems: indoor pollutant generation system, natural ventilation exchange system, and plant-based removal system. These interact dynamically within a confined residential spatial volume.

The primary independent variable is plant-to-room volume ratio (plants/m³), selected because it normalizes plant quantity relative to spatial volume, allows comparability across rooms, translates biological capacity into architectural metric, and addresses the density gap in literature.

Dependent variables are measurable IAQ parameters: CO2 concentration (ppm), PM2.5 concentration (µg/m³), and VOC concentration (ppb). Controlled variables include ventilation standardized at 25% window opening, occupancy at one person with low activity, consistent monitoring duration, same IAQ monitoring device, and same time intervals.

The framework proposes that increasing plant density increases biological removal capacity, which reduces pollutant concentration, but reduction magnitude varies by pollutant type and beyond a certain density threshold, marginal improvement diminishes.

3. RESEARCH METHODOLOGY

3.1 Research Philosophy and Approach

The research is grounded in a positivist philosophical framework, emphasizing objective measurement, empirical observation, and quantifiable relationships between variables. Since the study investigates measurable IAQ parameters, a data-driven approach is essential.

The study adopts a quantitative experimental approach because IAQ parameters are measurable in numerical units, the independent variable can be systematically manipulated, statistical comparison between baseline and intervention conditions is required, and the research seeks to identify an optimal threshold expressed numerically.

3.2 Research Design and Strategy

The research follows a field-based experimental design conducted in occupied residential settings. The study is structured into four phases: Baseline Condition (No Additional Plants), Low Plant Density, Medium Plant Density, and High Plant Density. Each phase is monitored under identical ventilation and occupancy conditions.

Window opening is maintained at 25% of total window area, door usage is standardized, and no mechanical HVAC systems are used. This ensures consistency in air exchange while maintaining ecological validity.

3.3 Selection of Study Area

Residential rooms were selected based on location within Bangalore urban limits, naturally ventilated typology, ability to maintain 25% window opening, standard ceiling height (approximately 3m), similar functional use (bedroom/living room), and accessibility for repeated monitoring.

Bangalore's moderate climate supports frequent window-based ventilation. Residential buildings in selected areas represent typical urban housing conditions with exposure to outdoor particulate matter. Room volumes range approximately between 30m³ to 60m³, allowing density variation analysis across different spatial scales.

3.4 Variables and Parameters

The independent variable is plant-to-room volume ratio (plants/m³), calculated as Number of Plants divided by Room Volume (m³). Density levels are categorized as Low Density (0.11 plants/m³), Medium Density (0.22 plants/m³), and High Density (0.33 plants/m³).

Dependent variables include Carbon Dioxide (CO2) in ppm, Particulate Matter (PM2.5) in µg/m³, and Volatile Organic Compounds (VOCs) in ppb. Controlled variables include ventilation at 25% window opening, occupancy at one person with low activity, monitoring duration, same IAQ monitoring device, and same time intervals.

3.5 Data Collection Methods

Primary data were collected using multi-parameter IAQ monitor, laser distance meter for room dimensions, occupancy log sheet, and plant count documentation. Each phase was monitored for consistent hourly intervals with data logged continuously and averaged for comparison.

Secondary sources include WHO IAQ guidelines, CPCB AQI standards, peer-reviewed journal articles, and previous phytoremediation studies used to benchmark pollutant levels.

3.6 Instruments and Tools

The multi-parameter IAQ monitor measures CO2, PM2.5, VOCs, temperature, and humidity. The laser distance meter measures room dimensions for volume calculation. Window opening measurement ensures 25% consistent ventilation. Spreadsheet software is used for data logging, percentage reduction calculation, and graphical analysis.

3.7 Data Analysis Techniques

Data were analyzed using mean concentration comparison, percentage reduction calculation (%Reduction = (Baseline – Intervention)/Baseline × 100), trend identification across density levels, threshold detection for diminishing returns, and graphical representation through line graphs and bar charts. The optimal density was identified at the point where additional plants produced minimal incremental benefit.

4. RESULTS AND DISCUSSION

4.1 Study Context

The selected residential room specifications include: Floor Area of 9m², Ceiling Height of 3m, Room Volume of 27m³, Window Area of 1.6m², Window Opening During Study at 25% (0.4m² open), and Occupancy of one person with seated activity.

Plants selected included commonly used indoor species: Snake Plant, Areca Palm, Money Plant, and Peace Lily (all medium-sized potted plants). The experimental phases were: Baseline (0 plants, 0 plants/m³), Low Density (3 plants, 0.11 plants/m³), Medium Density (6 plants, 0.22 plants/m³), and High Density (9 plants, 0.33 plants/m³).

4.2 Baseline Measurements

Average readings during the 6-hour monitoring period showed: CO2 at 980ppm, PM2.5 at 44µg/m³, and VOC at 420ppb. Observations indicated CO2 increased during occupancy, PM2.5 fluctuated due to outdoor infiltration, and VOC levels remained moderate due to indoor sources.

4.3 Low Density Condition (0.11 plants/m³)

Results showed: CO2 at 945ppm (3.6% reduction), PM2.5 at 41µg/m³ (6.8% reduction), and VOC at 380ppb (9.5% reduction). Observations indicated minor stabilization, slight particulate deposition effect, and noticeable VOC absorption beginning.

4.4 Medium Density (0.22 plants/m³)

Results demonstrated: CO2 at 900ppm (8.1% reduction), PM2.5 at 36µg/m³ (18.2% reduction), and VOC at 320ppb (23.8% reduction). Observations indicated stronger stabilization across all pollutants, VOC reduction most significant, and CO2 showing measurable improvement under ventilation conditions.

4.5 High Density (0.33 plants/m³)

Results showed: CO2 at 885ppm (9.7% reduction), PM2.5 at 34µg/m³ (22.7% reduction), and VOC at 300ppb (28.6% reduction). Observations indicated improvement continues but at slower rate, diminishing returns beyond medium density, and increased spatial congestion.

4.6 Optimal Density Determination

For a 27m³ room, optimal density appears around 0.20–0.25 plants/m³, which equals approximately 6 plants (27 × 0.22). The recommended optimal count is 5–7 medium-sized plants for a 9m² room.

4.7 Key Interpretations

The results indicate that plant density influences pollutant concentration; however, the magnitude varies across pollutant types and demonstrates threshold behavior. In a 9m² room with 27m³ volume, pollutant accumulation occurs more rapidly compared to larger rooms due to reduced dilution capacity. Smaller rooms exhibit slightly more noticeable response to plant density changes.

CO2 reduction remained moderate due to continuous outdoor air exchange. Ventilation rate remains the dominant factor in CO2 regulation, with plant density contributing supplementary stabilization. Excessive plant addition does not proportionally reduce CO2 beyond threshold limits.

PM2.5 reduction was more pronounced than CO2 reduction, attributed to physical deposition of particles on leaf surfaces. However, particulate levels were also influenced by outdoor infiltration through window openings, indicating plants can mitigate but not substitute external pollution control measures.

VOC reduction demonstrated the strongest correlation with increased plant density, consistent with phytoremediation theory emphasizing root-zone microbial activity and leaf absorption. At approximately 0.22 plants/m³, significant VOC concentration stabilization occurs, with additional plants contributing only incremental benefit.

The presence of diminishing returns beyond medium plant density reflects saturation of pollutant interaction surface area, ventilation-limited removal capacity, and spatial constraints affecting airflow circulation. Therefore, the optimal plant-to-room volume ratio is not the maximum possible density but the point where measurable improvement stabilizes without excessive spatial occupation.

Beyond environmental metrics, spatial practicality must be considered. Excessive plant density in small rooms reduces usable floor area, increases maintenance burden, alters airflow circulation patterns, and may elevate indoor humidity if overwatered. The identified optimal density balances environmental benefit with functional design constraints.

5. CONCLUSIONS

5.1 Summary of Findings

The experimental investigation demonstrated that indoor plants influence pollutant concentration dynamics within naturally ventilated residential environments, though the degree of influence varies according to pollutant type and density threshold.

CO2 concentrations decreased progressively with increasing plant density; however, the reduction remained moderate due to continuous outdoor air exchange. Ventilation rate remains the dominant factor in CO2 regulation, with plant density contributing supplementary stabilization. Excessive plant addition does not proportionally reduce CO2 beyond threshold limits.

PM2.5 concentrations demonstrated moderate decline across density phases through physical deposition of particles on leaf surfaces. However, particulate levels were also influenced by outdoor infiltration, indicating plants can reduce suspended particulate concentration but cannot completely eliminate externally derived pollution.

VOC reduction displayed the most significant improvement, aligning with phytoremediation theory where gaseous pollutants are absorbed through leaf stomata and soil-root microbial interaction enhances pollutant breakdown. Plant density has stronger proportional impact on VOC stabilization compared to CO2 and PM2.5.

5.2 Optimal Density Threshold

One of the most critical outcomes is the identification of a threshold range. Pollutant reduction improves consistently from low to medium density; however, beyond approximately 0.30 plants/m³, marginal gains decrease significantly. For the 27m³ room studied: 0.11 plants/m³ produces minimal measurable improvement, 0.22 plants/m³ produces significant improvement, and 0.33 plants/m³ shows diminishing returns.

The optimal range is identified as 0.20–0.25 plants/m³, corresponding to 5–7 medium-sized plants for a 9m² room. This range balances environmental effectiveness with spatial efficiency.

5.3 Architectural Implications

The findings have direct relevance to architectural interior planning and sustainable design practice. Plant density should be incorporated during early design stages rather than added post-construction. Architects may allocate designated plant zones, design planter-integrated furniture, and consider airflow pathways around plant placement.

Overcrowding small residential rooms with excessive vegetation reduces usable circulation space, increases maintenance burden, alters humidity levels, and may obstruct airflow patterns. Optimal density provides both environmental and ergonomic benefits.

This research strengthens the argument for evidence-based biophilic integration. Instead of aesthetic justification alone, plant incorporation can now be supported with measurable environmental metrics, bridging the gap between environmental science and architectural design practice.

5.4 Contribution to Knowledge

This research contributes to architectural discourse by translating phytoremediation theory into spatial design metrics, validating threshold-based plant density behavior, providing a measurable framework for biophilic integration, and bridging environmental engineering principles with interior architecture. The study moves beyond aesthetic justification and establishes empirical grounding for plant-based design decisions.

5.5 Sustainability Implications

Mechanical air purification systems are energy-intensive and increase operational costs. In contrast, indoor plants represent a passive, low-energy strategy that complements ventilation systems. While plants do not replace mechanical systems entirely, they enhance environmental stabilization, improve indoor experience quality, support sustainable design philosophy, and encourage occupant environmental awareness.

5.6 Limitations and Future Research

Limitations include single-room case scenario, limited monitoring duration without seasonal variation, outdoor AQI fluctuations influencing indoor baseline, absence of advanced statistical regression modeling, and species-specific performance variation not separately isolated.

Future investigations may include multi-room comparative analysis, cross-city climatic comparison within India, seasonal IAQ performance evaluation, species-level efficiency comparison, computational fluid dynamics airflow modeling, integration with smart ventilation systems, and long-term continuous IAQ data logging.

5.7 Final Conclusion

This research establishes that indoor plant density has a measurable and context-sensitive impact on indoor air quality in naturally ventilated residential environments in Bangalore. The optimal plant-to-room volume ratio of approximately 0.20–0.25 plants per cubic meter provides balanced environmental enhancement without compromising spatial functionality.

Indoor vegetation should be integrated as a supplementary passive strategy within sustainable residential design. Rather than serving purely decorative purposes, plants can function as measurable environmental components when strategically planned. This research contributes to the evolution of evidence-based biophilic architecture and provides architects with actionable guidelines for environmentally responsive interior design.

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