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Research Article

Optimizing indoor air quality in sustainable homes: A simulation-based evaluation of VOC emissions from bamboo-based materials

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Abstract

This study presents a simulation-based assessment of indoor air quality (IAQ) in residential buildings using bamboo-based construction materials, with a focus on volatile organic compound (VOC) emissions. Nine case studies were modeled using CONTAM software, examining variations in material selection, adhesive type, ventilation rate, and indoor temperature. The baseline case, using oriented strand board (OSB) and cork flooring, produced peak total VOC (TVOC) levels of 3.775 mg/m^3 and formaldehyde concentrations up to 1.25 mg/m^3, exceeding recommended thresholds despite sufficient ventilation. Replacing OSB and cork with laminated bamboo panels and flooring bonded with soy-based adhesives resulted in a 70–80% reduction in VOC emissions, with TVOC levels dropping to 0.88 mg/m^3 and formaldehyde concentrations below 0.3 mg/m^3. In contrast, bamboo bonded with melamine urea formaldehyde (MUF) adhesives showed moderate improvements, with TVOC at 1.02 mg/m^3. Elevated indoor temperatures increased VOC levels by over 30%, while enhanced ventilation reduced them by 25–35%. Results from a mass balance analytical model aligned with simulation trends, supporting model validity. The findings demonstrate that combining low-emission bamboo materials with optimized ventilation offers a viable strategy for achieving healthier indoor environments, supporting sustainable and occupant-focused residential design.

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1. Introduction

Indoor air quality (IAQ) is a critical determinant of human health and comfort, especially in urban environments where individuals spend approximately 90% of their time indoors [1]. IAQ encompasses the quality of air within and around buildings and structures, directly affecting the health and comfort of occupants [2]. Poor IAQ is associated with a spectrum of health concerns, ranging from respiratory irritation and allergic reactions to more severe long-term impacts such as asthma, neurological disorders, and cancer [3]. Among the contributors to indoor air pollution, volatile organic compounds (VOCs) play a dominant role due to their ubiquitous presence in common building materials, furniture, adhesives, and coatings [4]. As global efforts toward sustainable building and low-carbon materials accelerate, there is growing interest in alternative building materials that minimize indoor emissions without compromising performance or aesthetic value [5].

Bamboo has gained traction as a promising renewable material in the construction industry due to its rapid growth cycle, high strength-to-weight ratio, and environmental benefits such as carbon sequestration and biodegradability [6]. Recent advancements in engineered bamboo products such as laminated bamboo panels and bamboo flooring have enabled their broader application in

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interior architecture [7]. However, despite their ecological appeal, the impact of bamboo-based materials on IAQ remains underexplored, particularly in relation to VOC emissions under varying ventilation and thermal conditions [8]. Adhesives used in laminated bamboo, including melamine urea formaldehyde (MUF) and soy-based alternatives, can significantly influence VOC profiles, further complicating material selection for green design [9].

Traditional IAQ research has often focused on monitoring pollutant concentrations in existing buildings, but recent methodological shifts emphasize simulation-based modelling as a powerful tool for design-stage IAQ evaluation [10]. Models such as CONTAM, developed by the National Institute of Standards and Technology (NIST), allow for detailed assessment of airflow, contaminant dispersion, and thermal interactions across a variety of material and operational scenarios [11]. This tool supports early design-stage decisions by modelling how contaminants disperse indoors and predicting pollutant levels before a building is occupied. CONTAM can also estimate individual exposure by integrating occupancy schedules with predicted pollutant concentrations [12]. Its applications span infiltration studies [13,14], pollutant transport simulations [15], and occupant exposure analysis [16,17]. Despite its versatility, a known limitation is the assumption of uniform contaminant concentration within each zone [18]. By leveraging such simulations, researchers and designers can test the influence of material substitutions, ventilation strategies, and indoor environmental parameters without incurring the costs of physical experimentation.

This study addresses a critical research gap by systematically evaluating the effects of bamboo interior materials on IAQ using simulation-based modelling. The investigation is structured around multiple case studies, including configurations with and without bamboo elements, and further explores the role of adhesive type, flooring systems, mechanical ventilation rates, and indoor temperature conditions. The aim is to quantify how bamboo-based construction can contribute to reduced VOC emissions and improved IAQ performance in residential buildings. By bridging sustainable material science with IAQ simulation, this research contributes to the development of greener, healthier indoor environments in line with contemporary building performance goals.

2. Methodology

The methodology implemented in this research involved a simulation-based analysis to evaluate the impact of bamboo-based building materials on indoor air quality (IAQ), with a particular focus on the emission of volatile organic compounds (VOCs).

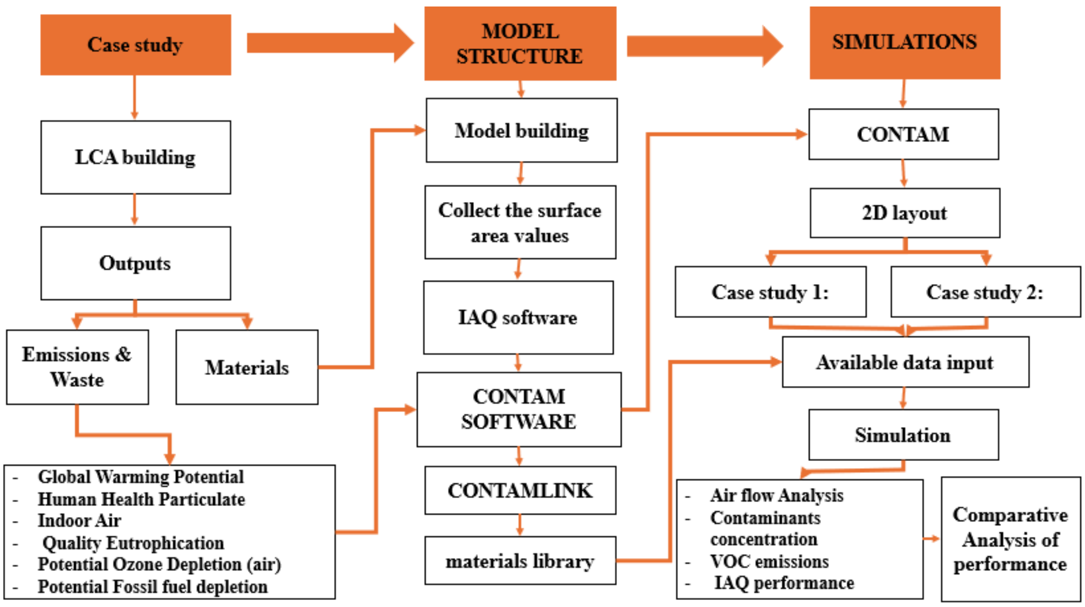

Fig. 1. Detailed simulation framework outlining data inputs, emission sources, material libraries, software integration, and analysis phases.

The study used CONTAM, a multizone indoor air quality and ventilation analysis software developed by the National Institute of Standards and Technology (NIST), as the primary simulation tool. The approach was structured into three main stages as in Fig. 1 and 2 present a case study selection, structural and IAQ model development, and simulation execution.

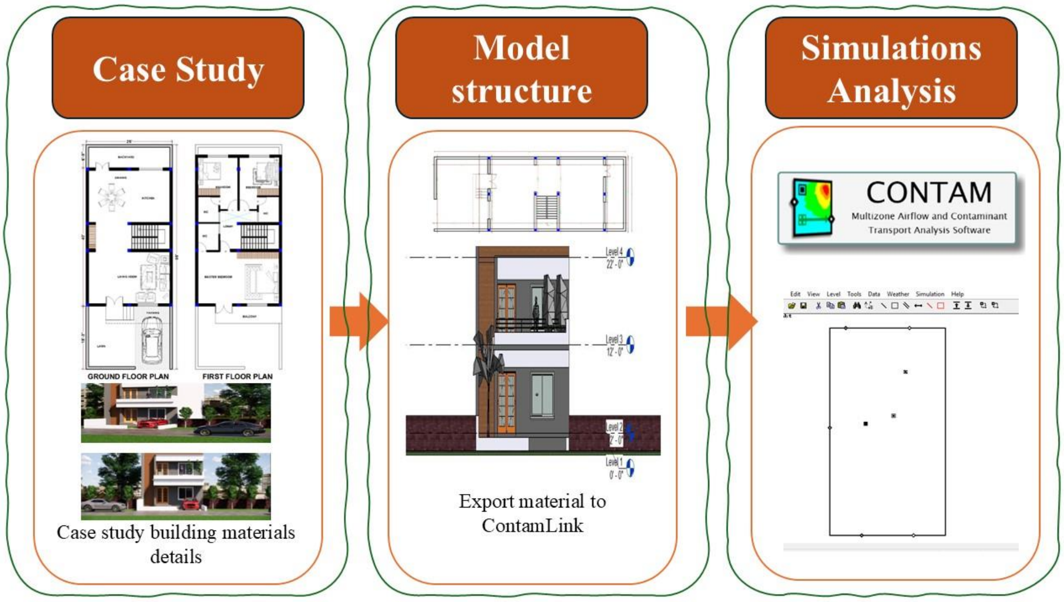

Fig. 2. Visual methodology workflow showing the transition from architectural modeling and material definition to IAQ simulation using CONTAM

In the first stage, a representative residential building was selected as a case study, including detailed architectural floor plans (ground and first floors) and exterior 3D renderings to establish the spatial and material configurations of the structure. Key materials used in the interior, such as bamboo-based panels and traditional timber, were documented for emission evaluation.

Table 1. Building and Simulation Setup Parameters in CONTAM

Parameter	Description/Value
Building Type	Residential, 2-story, timber frame (Jakarta proxy)
Total Floor Area	185 m^2
Indoor Volume (estimated)	518 m^3 (based on 2.8 m ceiling height)
Climate Zone	Temperate
Simulation Duration	8760 hours (full year)
Occupancy Schedule	6 a.m. – 10 p.m. (based on residential standards)
Ventilation System	Mechanical supply + natural infiltration
Ventilation Rate Range	30 – 138.3 L/s (based on simulation and SNI)
Modeling Software	Building: Autodesk Revit IAQ: CONTAM v3.4
Integration Tool	CONTAMLink v3.4
CONTAM Simulation Input	Multizone airflow + VOC emissions
Door Gap Flow Coefficient	0.001 (living–bedroom, always open)
Diffuser Flow Coefficient	0.005 (bedroom–corridor, night only)
Window Leakage Flow	0.002 (kitchen–outdoor, day only)

In the second stage, the architectural model was reconstructed in a CAD environment, where geometrical and structural information was integrated and prepared for export. The model was then converted using ContamLink, enabling the transfer of spatial and material data into the CONTAM environment. In the final stage, the model was imported into CONTAM software, a multizone indoor air quality simulation tool, to assess airflow patterns and VOC emission behavior under different conditions. The simulation focused on contaminant transport across rooms, reflecting the influence of material choice on indoor air quality. The building was modeled after a two-story light-frame timber residence representative of tropical residential design. Its geometric and spatial configurations were developed in Autodesk Revit and exported to CONTAM via CONTAMLink. Environmental parameters such as climate zone (temperate), occupancy schedules, ventilation strategies, and infiltration paths were specified based on standardized input datasets as in Table 1. The simulation was executed over a full-year duration (8760 hours) using an hourly time step to capture seasonal variations in pollutant behavior.

CONTAM was selected for its proven multizone simulation capabilities, and its ability to efficiently assess VOC transport and ventilation dynamics across large timeframes (e.g., full-year simulations) with minimal computational demand. Its computational effectiveness and predictive accuracy have been substantiated through real-world applications and case studies [18–20]. Another prominent tool in the domain of fluid dynamics is Computational Fluid Dynamics (CFD), which offers a detailed numerical approach to modelling gas behaviour and flow interactions within complex environments. CFD has proven to be dependable in modelling pollutant dispersion and airflow in sensitive indoor areas, including healthcare facilities [21], food preparation spaces [22], and research laboratories [23]. However, when dealing with buildings that feature numerous rooms and architectural complexity, CFD simulations become resource-intensive and time-consuming. In contrast, CONTAM provides a more streamlined and resource-efficient option, enabling faster analysis with simplified input parameters [24]. Given these advantages, CONTAM is often the preferred solution for evaluating airflow dynamics, pressure distributions, and indoor contaminant pathways. While CFD models offer spatial resolution, CONTAM enables full-building analysis of contaminant movement and occupant exposure, making it suitable for early-stage material and IAQ evaluation [25,26].

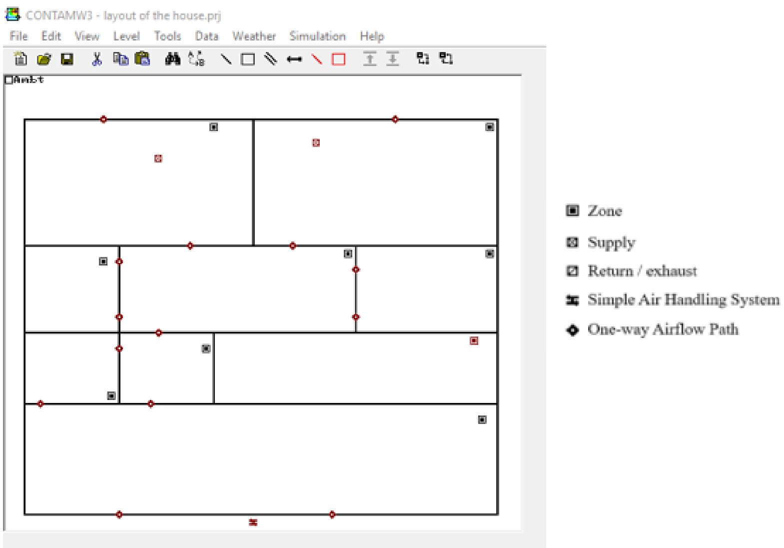

Fig. 3. Multizone layout of the case study house modeled in CONTAM for airflow and VOC simulation

The layout in CONTAM of the house, taken into consideration in this study, is shown in Fig. 3. The Figure presents the multizone layout of the residential case study building as modeled in CONTAM software. Each outlined rectangle represents a distinct indoor zone, such as bedrooms, living spaces, or service areas. The diagram includes key airflow components: supply vents (black squares), return/exhaust points (striped squares), a simple air handling system (fan icon), and one-way airflow paths (red diamonds), which simulate air movement between zones. This schematic serves as the foundation for simulating ventilation performance and VOC distribution throughout the house under various material and environmental scenarios. The simulation focused on comparing multiple case studies that varied in material configurations. The baseline case used conventional materials like oriented strand board (OSB), gypsum wallboard, and cork flooring. Alternative scenarios incorporated laminated bamboo panels and bamboo flooring, bonded with either soy-based or melamine urea formaldehyde (MUF) adhesives. This allowed for a comparative analysis of emissions across both low-emission and standard material options.

The first case study was designed as the baseline configuration, where the building envelope and internal finishes reflected conventional construction practices. Wall assemblies consisted of oriented strand board (OSB) and gypsum board, while flooring materials included cork and gypsum-based products as in Fig. 4. This configuration provided a reference scenario against which alternative material strategies could be evaluated. All material data, including emission rates, were collected from manufacturers' specifications and peer-reviewed literature, ensuring consistency with industry standards.

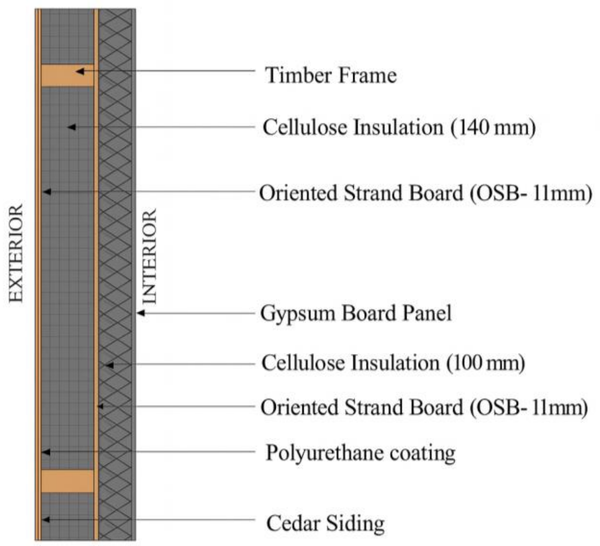

Fig. 4. Wall section of case study 1 (timber wall frame structure)

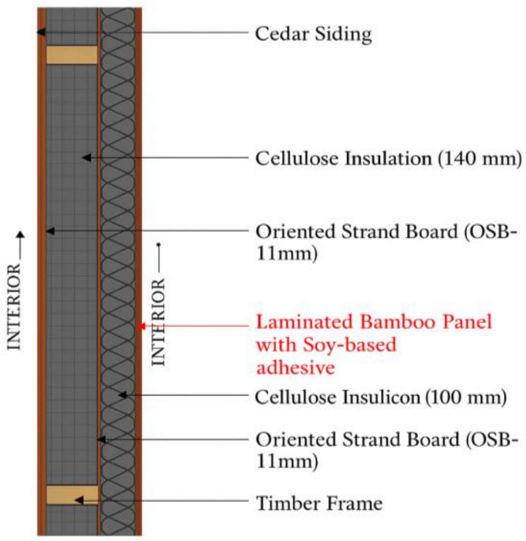

Fig. 5. Wall section of case study 2

In the second case study, the research introduced bamboo-based construction materials to replace conventional wall and floor components. Laminated bamboo panels and flooring were modelled in place of OSB and cork as in Fig 5, allowing for a comparative assessment of material influence on indoor air quality. This case study included several sub-scenarios that differed based on the type of adhesive used in the bamboo composites. These included melamine urea formaldehyde (MUF) adhesives, soy-based alternatives, and natural low-emission binders. Each sub-case retained the same architectural and volumetric parameters as the baseline model, ensuring that observed differences could be attributed solely to material substitutions.

The third case study extended the simulation analysis by varying key environmental parameters within the same building configuration. This phase explored the impact of modified ventilation rates and indoor temperatures on airflow and pollutant behaviour. Three environmental scenarios were modelled: one with reduced natural ventilation, another with increased indoor temperature, and a third with decreased temperature. These variations were intended to reflect realistic fluctuations in building operation and climate, and to assess how such conditions interact with material emissions. Table 2 presents the material configurations used across the different case studies in this research. It outlines the combinations of wall and floor materials, adhesive types, and known sources of volatile organic compounds (VOCs).

To accurately simulate inter-zonal air movement within the residential case study model, airflow connections were defined between key building spaces based on typical architectural layouts and ventilation behaviours. Airflow from the living room to the bedroom was modelled through a door gap with a flow coefficient of 0.001, and this pathway was assumed to be "always open," representing standard internal door conditions during occupancy hours. A second inter-zone connection was specified between the bedroom and corridor using a diffuser-type flow mechanism, with a flow coefficient of 0.005. This connection operated under a "night only" schedule, reflecting mechanical system settings for enhanced nocturnal ventilation and thermal comfort. Additionally, a pathway was defined from the kitchen to the outdoor environment, simulating leakage through a window. This connection used a flow coefficient of 0.002 and was set to operate during the "day only" period, mimicking occupant behaviour of window opening for natural ventilation and door removal during cooking activities. These airflow configurations were incorporated into the CONTAM model to realistically capture pollutant transport dynamics across different building zones and enhance the fidelity of the IAQ simulation.

Table 2. Material configurations across case studies

Case Study	Wall Material	Floor Material	Adhesive Type	Known VOC Sources
CS1	OSB + Gypsum	Cork	–	OSB, cork
CS1.1	OSB + Gypsum	–	–	OSB
CS2.0	Bamboo + OSB	Partial Cork	Soy-based	Reduced
CS2.1	Bamboo + OSB	None	Soy-based	Minimal
CS2.2	Bamboo + OSB	–	MUF	Elevated
CS2.3	Full Bamboo	Bamboo	Soy-based	Lowest
CS3.0–3.2	Full Bamboo	Bamboo	MUF	Conditional on environment

Table 3 summarizes the zone-specific ventilation configurations used in the CONTAM model, including supply and exhaust pathways, as well as estimated air exchange rates for each room. These configurations reflect realistic residential ventilation behaviours, combining both mechanical and natural mechanisms. The values were selected based on common occupancy schedules and reflect performance ranges validated in literature and local building codes. Table 4 presents the emission characteristics of selected building materials used as input parameters for the CONTAM simulation. It includes total volatile organic compound (TVOC) and formaldehyde emission rates, expressed in $mg/m^2 \cdot h$, based on established literature sources. Emission rates for total VOCs and formaldehyde were based on literature values and material safety data sheets (MSDS). These values were assigned as emission factors in the CONTAM simulation environment and governed the mass transfer of pollutants from surfaces into the indoor environment.

Simulation scenarios were systematically structured to isolate the effects of materials and environmental controls as in Table 5. The primary control variables were indoor temperature and mechanical ventilation rate. While Case Study 1 simulated conventional material use, Case Study 2 explored bamboo integration, and Case Study 3 tested thermal and ventilation sensitivities. Environmental variations, including indoor temperature (25–30°C) and ventilation rates (59.8–138.3 L/s), were selected based on regional climate conditions (Jakarta proxy) and Indonesian SNI ventilation standards for residential buildings (SNI 03-6572-2001) [31]. This ensures that the simulation output reflects realistic residential environments in tropical regions

Table 3. Distribution of ventilation system by room and operation type

Description	Supply Inlet	Exhaust Outlet	Air Exchange Rate (1/h)
Living Room	Mechanical diffuser	Corridor return	0.5–0.7
Bedroom	Natural infiltration	Mechanical (night only)	0.4–0.6
Kitchen	Window (day only)	Mechanical vent hood	1.5–2.0
Bathroom	Mechanical vent grille	Mechanical fan	2.0–3.0
Corridor	Indirect via doors	Central return shaft	0.6–0.8

The simulation outputs included time-series data for average airflow rates and total VOC emissions (TVOC) over a one-year period. Data analysis was conducted by comparing average values across different scenarios and visually interpreting trends in air flow and emission rates using comparative graphs and box plots. The methodology provided a robust framework for assessing the potential of bamboo materials in improving indoor air quality. It enabled the identification of both material-related and environmental factors influencing VOC emissions in residential buildings.

Table 4. Material emission factors (Input to CONTAM)

Material	TVOC Emission Rate (mg/m^2·h)	Formaldehyde (mg/m^2·h)	Source
OSB	0.5	0.2	[27]
Cork	0.6	0.3	[28]
Bamboo (Soy Adhesive)	0.1	0.03	[29]
Bamboo (MUF Adhesive)	0.3	0.1	[29]
Timber	0.4	0.15	[30]

Table 5. Simulation scenarios and control variables

Case Study	Temp. (°C)	Ventilation (L/s)	Duration	Purpose
CS1	25	59.8–126.5	1 year	Baseline reference
CS2.1	25	59.8–126.5	1 year	Material substitution
CS3.1	30	59.8–133.3	1 year	Temp stress test
CS3.2	25	87.3–138.3	1 year	Dilution strategy

To validate the simulation-based results generated by CONTAM, an analytical approach was adopted using a well-established indoor air quality model based on the principle of mass balance in a well-mixed zone. This method provides a simplified yet effective means to estimate time-dependent concentrations of volatile organic compounds (VOCs) within an enclosed indoor environment, given known emission and ventilation characteristics [32]. The well-mixed zone model assumes that indoor air is perfectly mixed and that pollutant concentrations are spatially uniform across the space[32,33]. The change in VOC concentration over time due to a continuous emission source is governed by the following mass balance as in Eq. (1).

$$C(t) = \frac{E}{Q}\left(1 - e^{\frac{-Q}{V}t}\right) \tag{1}$$

Where, C(t): the VOC concentration at time t (mg/m^3), E: the emission rate from indoor surfaces (mg/h), Q: the ventilation rate (m^3/h), V: the indoor air volume (m^3), t: the duration of accumulation (h).

For this study, the indoor volume (V) was estimated at 518 m^3, based on a two-story residential floor area of 185 m^2 and an average ceiling height of 2.8 meters. The ventilation rate (Q) was calculated using airflow rates extracted from simulation results, typically ranging from 455.4 to 497.9 m^3/h, depending on the case scenario. Emission rates (E) were estimated based on the dominant material configuration, varying from 12 mg/h for full bamboo with soy adhesives to 70 mg/h for conventional OSB and cork. The time frame (t) was set to 8 hours, simulating typical daily occupancy exposure. The results of the analytical estimates were then compared with the peak total VOC (TVOC) concentrations derived from the CONTAM simulations.

4. Results and Discussion

4.1 Case Study 1: Baseline Configuration

The analysis of Case Study 1, which utilized conventional building materials including OSB wallboards, gypsum panels, and cork flooring, revealed significant temporal variability in both airflow and VOC concentrations. The average airflow rate across the year ranged from 59.8 L/s in February to a peak of 126.5 L/s in May, with a clear upward trend from early spring to late summer, followed by a gradual decline toward the end of the year as in Fig. 6. These values are consistently above the SNI-based minimum threshold of 30 L/s for residential ventilation [34], indicating that the mechanical system in this configuration delivers sufficient ventilation under standard operating conditions.

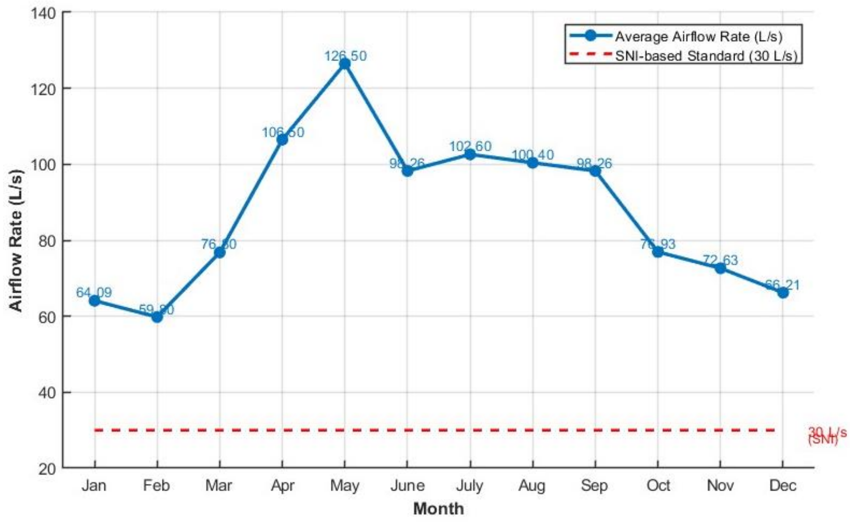

Fig. 6. Monthly average airflow rates for the baseline configuration, showing mechanical system performance across the year (Case Study 1)

Despite adequate ventilation rates, VOC concentrations in the case study remained above acceptable thresholds during most months. As shown in Fig. 7, total VOC (TVOC) levels from all materials peaked at 2.330 mg/m^3 in August, with the lowest level of 1.465 mg/m^3 recorded in December. These values significantly exceed the commonly cited benchmarks of 0.3 mg/m^3 for "Good" TVOC and 0.6 mg/m^3 for "Acceptable" TVOC, indicating persistent air quality concerns. Among individual materials, timber consistently exhibited the highest TVOC contribution, followed by OSB and gypsum, all of which remained above acceptable limits throughout the year. Although cork flooring contributed minimally to total TVOC, it remained the dominant source of formaldehyde, with relatively stable values across the months. These results highlight that even with compliant airflow design, pollutant levels can remain elevated due to material-based emissions, emphasizing the need to consider source control in addition to ventilation when aiming for healthier indoor environments.

4.2 Case Study 1.1: Impact of Cork Flooring Removal

In Case Study 1.1, cork flooring was excluded from the original material configuration to isolate its impact on indoor VOC levels, while the wall materials remained unchanged. As illustrated in Fig. 8, this material adjustment had no effect on the mechanical ventilation system's performance, as the average monthly airflow profile mirrored that of Case Study 1. The airflow rate peaked in May at 126.5 L/s and followed a consistent seasonal pattern, with values well above the SNI-based standard of 30 L/s throughout the year. This consistency confirms that changes in interior materials did not alter the ventilation dynamics, enabling a focused evaluation of VOC source reduction due solely to flooring modification.

However, Fig. 9 illustrates the VOC emission trends following the exclusion of cork flooring in Case Study 1.1. A notable improvement in indoor air quality was observed, with the annual peak of total VOC (TVOC) concentrations reduced from 3.775 mg/m^3 in the baseline scenario to 2.33 mg/m^3 in August. Formaldehyde levels—primarily linked to cork materials—also decreased significantly, peaking at 0.52 mg/m^3, which, while still exceeding the formal SNI limit, reflects a substantial drop from Case Study 1. The seasonal pattern of emissions remained consistent, suggesting the observed reductions were directly tied to material substitution rather than changes in airflow. Furthermore, the VOC contributions from timber, OSB, and gypsum remained nearly identical to the original case, reinforcing that the overall improvement was due to the elimination of cork-based emissions. This outcome highlights the critical role of strategic material selection in managing indoor pollutant levels. Although the reduction did not bring VOC concentrations below recommended thresholds, it represents a meaningful step toward creating healthier indoor environments by targeting high-emission sources.

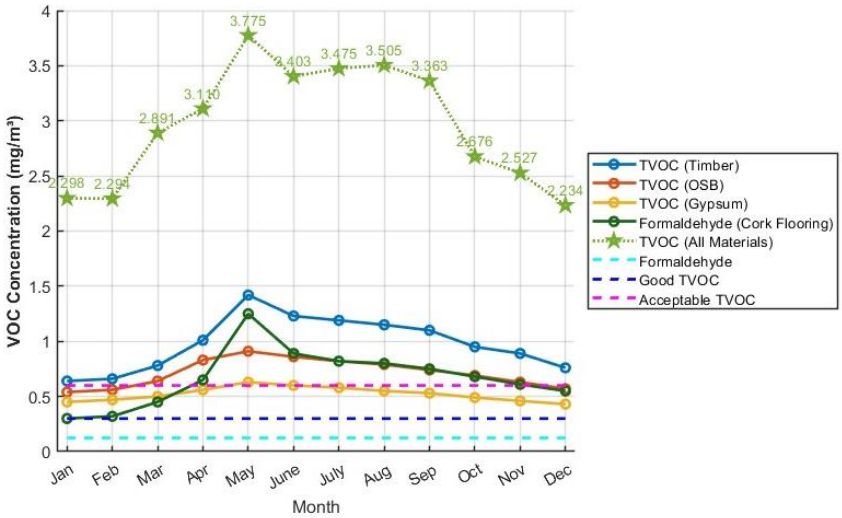

Fig. 7. VOC emission profile for the baseline case using OSB, gypsum, and cork flooring, highlighting monthly fluctuations in total VOC levels, Case Study 1

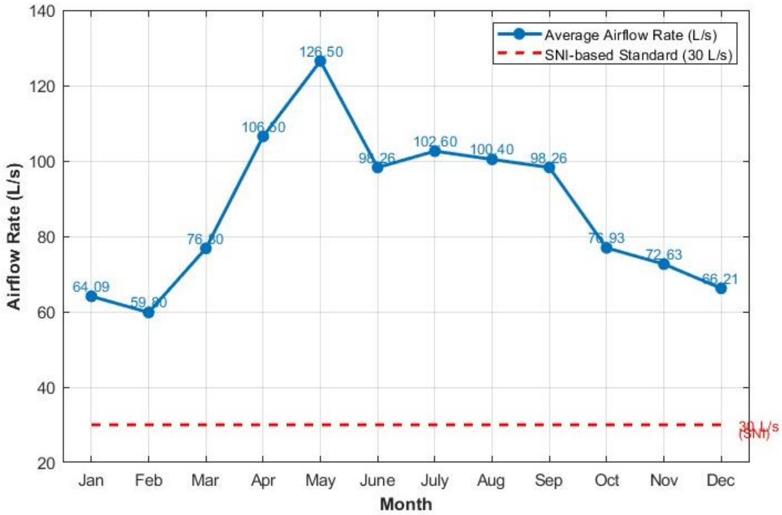

Fig. 8. Airflow rate trends following the removal of cork flooring, showing similar ventilation behavior to the baseline case (Case Study 1.1)

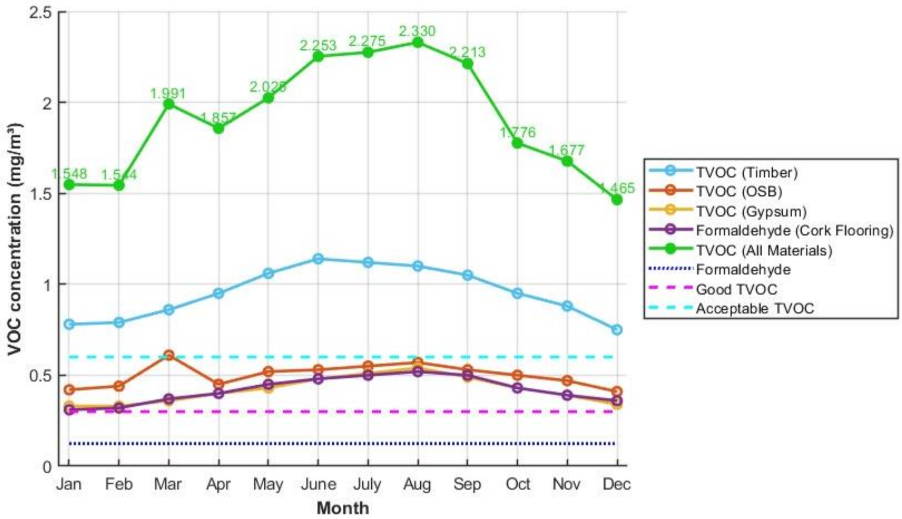

Fig. 9. VOC emission levels after removing cork flooring, demonstrating a significant reduction in total VOCs and formaldehyde concentrations (Case Study 1.1)

4.3 Case Study 2: Bamboo Material Substitution Scenarios

4.3.1 Case Study 2.0: Initial Bamboo Integration

In Case Study 2.0, laminated bamboo panels bonded with soy-based adhesives were introduced to replace conventional materials such as OSB boards and cork flooring. As shown in Fig. 10, the modification had no effect on the ventilation system, with monthly airflow rates mirroring those of previous case studies—ranging from 59.8 L/s in February to a peak of 126.5 L/s in May. Throughout the year, airflow remained well above the SNI standard of 30 L/s, confirming adequate ventilation performance.

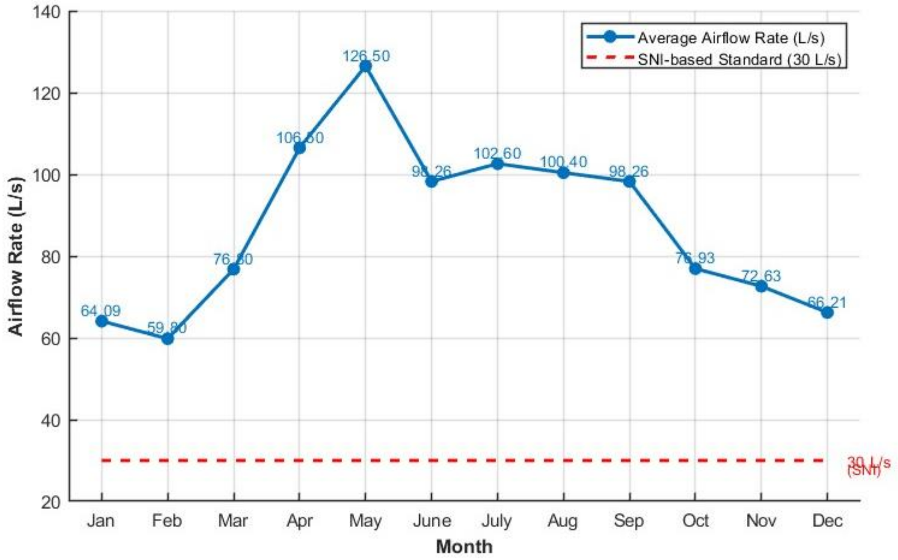

Fig. 10. Monthly average airflow rates for bamboo substitution scenarios, illustrating consistent ventilation performance across Cases 2.1–2.3.

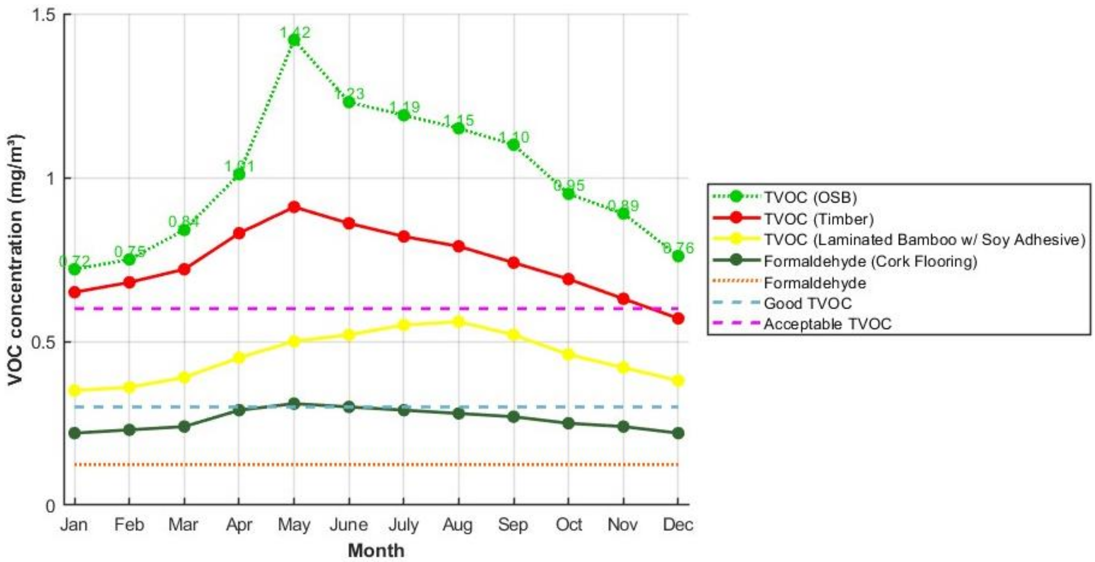

Fig. 11 VOC emission trends after partial integration of bamboo panels with soy-based adhesive, revealing improved IAQ over conventional materials (Case Study 2.0)

VOC emissions, illustrated in Fig. 11, showed a substantial reduction compared to the baseline. The peak TVOC level dropped to 1.23 mg/m^3 in May, significantly lower than the 3.775 mg/m^3 recorded in Case Study 1. Across all months, TVOC remained below 1.5 mg/m^3, with laminated bamboo panels emitting an average of 0.5 mg/m^3, demonstrating their low-emission profile. While OSB and timber still contributed to VOC levels, their impact was diminished. Additionally, formaldehyde emissions—previously elevated due to cork—were reduced as cork flooring was only partially retained. These findings underscore the effectiveness of using soy-based adhesives in bamboo construction to improve indoor air quality without compromising airflow efficiency.

4.3.2 Case Study 2.1: Full Removal of Cork Flooring

In Case Study 2.1, cork flooring was eliminated to further reduce formaldehyde and VOC emissions. As shown in Fig. 12, laminated bamboo panels bonded with soy-based adhesives maintained consistently low emission levels throughout the year. Timber remained a moderate contributor to TVOC but did not exceed 1.0 mg/m^3 in any month. Notably, OSB emissions showed further decline, particularly during the cooler months, reinforcing the sensitivity of material emissions to seasonal temperature variations. The complete removal of cork—a primary source of formaldehyde—resulted in a significant improvement in overall indoor air quality, even during peak summer months. These findings confirm that replacing high-emission materials with lower-emission alternatives such as laminated bamboo can meaningfully reduce pollutant loads, supporting healthier indoor environments without compromising material performance.

4.3.3 Case Study 2.2: Bamboo Panel with MUF Adhesive

In Case Study 2.2, laminated bamboo flooring bonded with melamine-urea-formaldehyde (MUF) adhesive was assessed to understand the impact of synthetic binders on indoor VOC levels. As shown in Fig. 13, the emission profile of timber and OSB remained consistent with previous cases, while bamboo with MUF adhesive exhibited notably higher VOC concentrations, with values peaking near 0.96–1.02 mg/m^3 during warmer months. Although formaldehyde levels remained below critical limits, a slight increase was observed compared to soy-based adhesive scenarios, indicating that MUF-based products contribute more significantly to VOC burdens. The results underscore the importance of adhesive choice in sustainable material selection. While MUF adhesives offer structural reliability, they compromise indoor air quality when compared to bio-based alternatives. These findings reinforce the necessity of evaluating not just the base material but also binding agents when designing for low-emission environments.

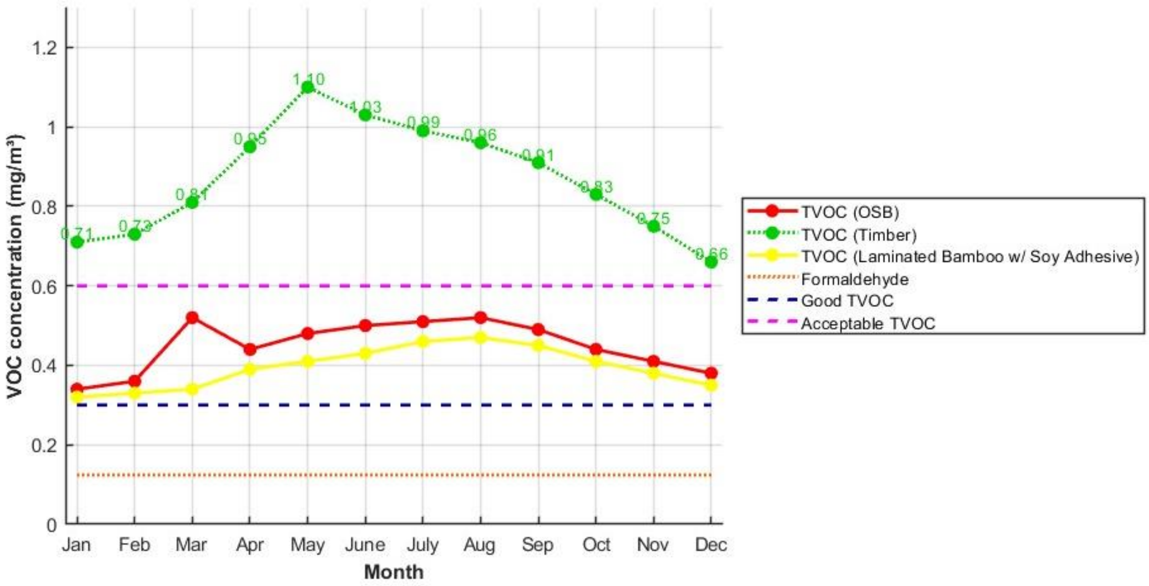

Fig. 12. VOC levels with complete replacement of cork flooring using laminated bamboo and soy adhesive, resulting in optimal IAQ performance (Case Study 2.1).

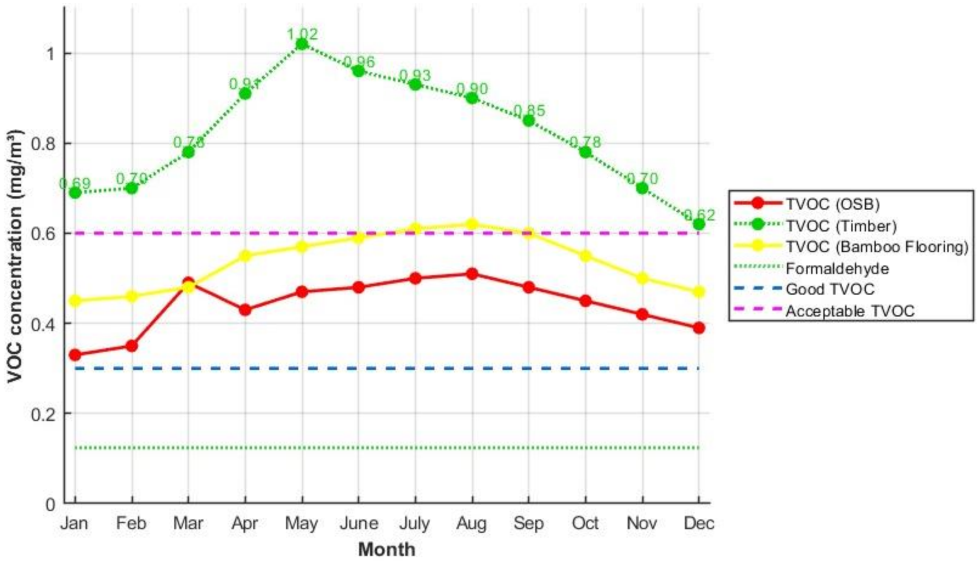

Fig. 13. VOC emission patterns with laminated bamboo using MUF adhesive, indicating higher pollutant levels compared to soy-based alternatives (Case Study 2.2)

4.3.4 Case Study 2.3: Bamboo Flooring Integration

In Case Study 2.3, laminated bamboo flooring was fully integrated alongside bamboo wall panels to assess the combined impact on indoor VOC emissions. As shown in Fig. 14, bamboo flooring consistently contributed lower TVOC levels than both OSB and timber across all months, with values remaining below 0.5 mg/m^3 throughout the year.

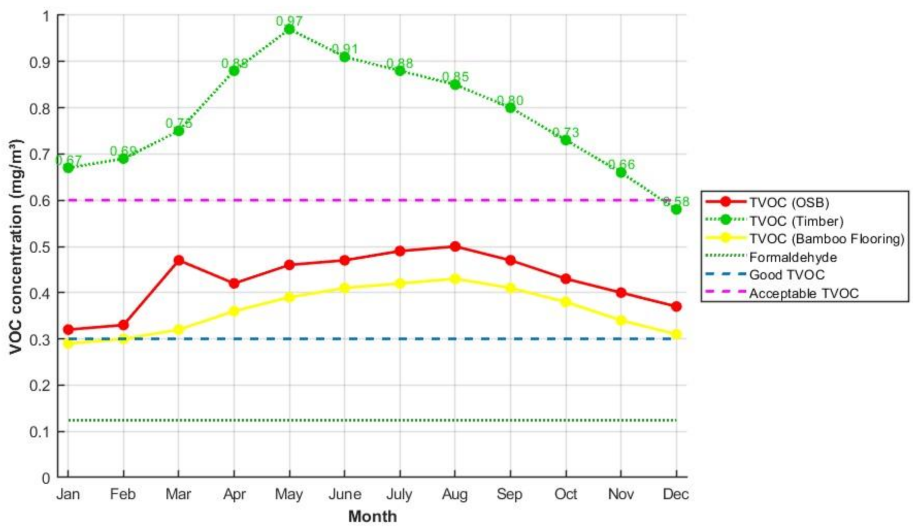

Fig. 14. Total VOC concentrations from full bamboo integration (walls and flooring), confirming cumulative emission reductions (Case Study 2.3)

These findings indicate that laminated bamboo, when used with low-emission adhesives, performs favorably as a sustainable interior finish. The combination of bamboo flooring and wall panels produced a cumulative reduction in pollutant emissions, highlighting the material's suitability for green building applications. This case reinforces the importance of pairing natural materials with optimized binders to achieve measurable improvements in indoor air quality. The results confirm that a holistic substitution strategy—targeting both surface and structural components—can yield superior environmental performance in residential interiors.

4.4 Case Study 3: Influence of Mechanical Ventilation and Temperature

4.4.1 Case Study 3.0: Bamboo Material with Standard Parameters

In Case Study 3.0, bamboo-based interior components, including laminated bamboo panels with melamine-urea-formaldehyde (MUF) adhesive and bamboo flooring—were analyzed under a fixed mechanical ventilation setting. As presented on Fig. 15, the monthly average airflow remained well above the SNI benchmark of 30 L/s, peaking at 138.3 L/s in May and reaching a minimum of 70.85 L/s in January, indicating stable mechanical system performance across seasonal variations.

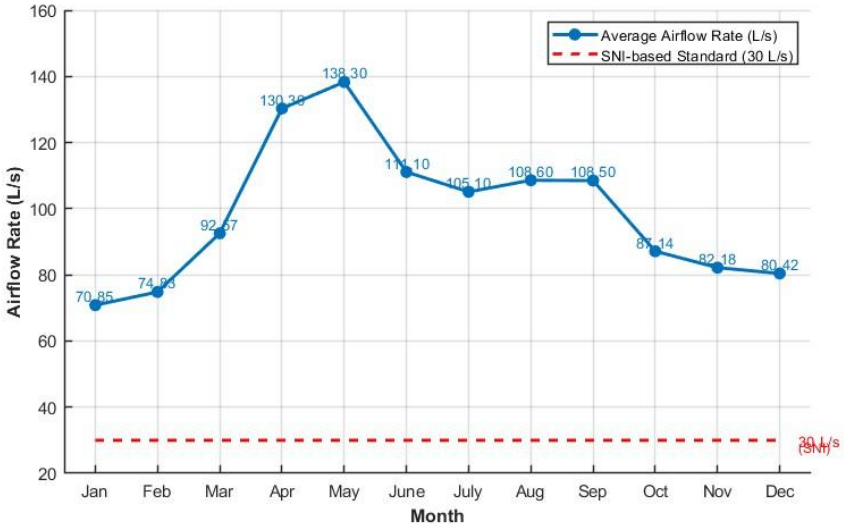

Fig. 15. Airflow behavior under standard environmental conditions for MUF-bonded bamboo configurations, reflecting seasonal ventilation performance (Case Study 3.0)

Despite adequate ventilation, VOC emissions varied by material, as shown on Fig. 16 Timber remained the highest contributor, peaking at 0.91 mg/m^3 in July before gradually declining. Laminated bamboo with MUF adhesive emitted moderate VOC levels ranging from 0.5 to 0.62 mg/m^3, with a maximum in August, slightly surpassing the “Acceptable” threshold of 0.6 mg/m^3. Meanwhile, bamboo flooring continued to perform favorably, maintaining VOC concentrations below 0.45 mg/m^3 throughout the year.

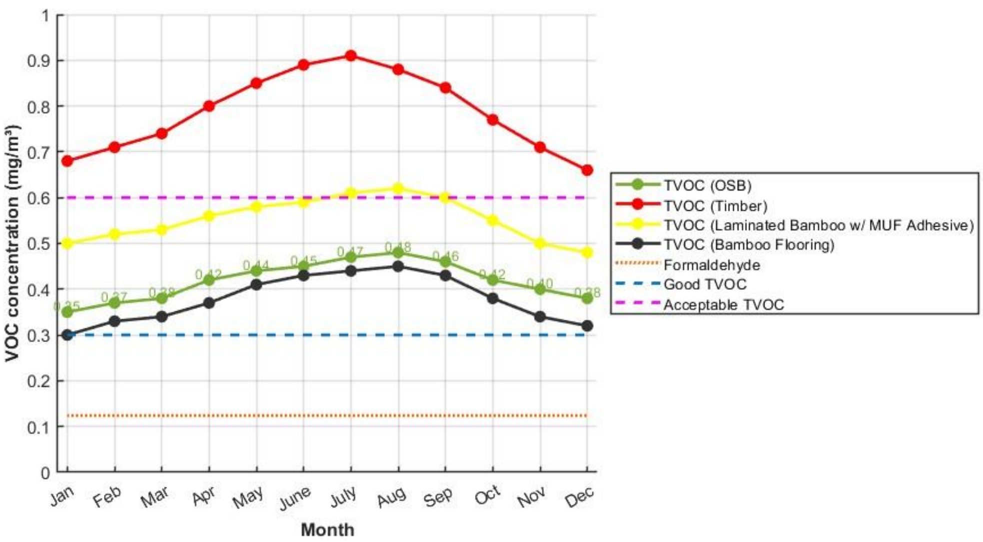

Fig. 16. VOC emission distribution from different material sources in a bamboo-based system under standard conditions (Case Study 3.0)

These outcomes suggest that although MUF-based adhesives enhance material durability, they also elevate indoor VOC emissions when compared to bio-based alternatives. The results reinforce the importance of selecting both sustainable base materials and low-emission binders to optimize indoor air quality while meeting structural performance goals. It is noted that VOC levels in certain configurations, including those using MUF adhesives or during high-temperature scenarios, still exceeded recommended IAQ thresholds. This suggests that material substitution alone is not sufficient, and must be complemented by thermal regulation and mechanical ventilation strategies to maintain optimal indoor air quality

4.4.2 Case Study 3.1: Increased Temperature Scenario

In Case Study 3.1, elevated indoor temperature conditions were simulated to evaluate their impact on VOC emissions, while maintaining the same mechanical ventilation setup as the baseline. As shown in Fig. 17, the airflow performance remained unchanged, peaking at 133.3 L/s in May, which confirms the stability of the system regardless of thermal variations.

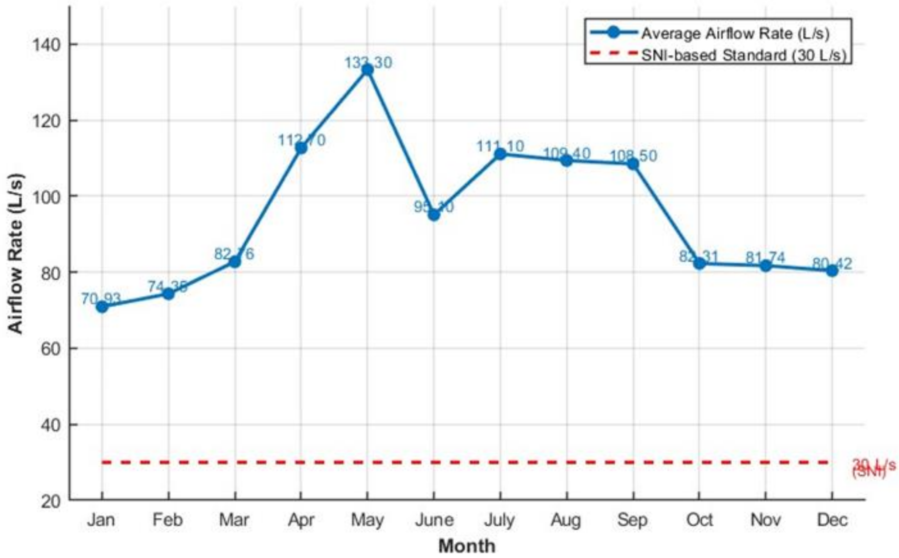

Fig. 17. Airflow rates during elevated temperature scenarios, showing consistent mechanical performance under thermal stress (Case Study 3.1)

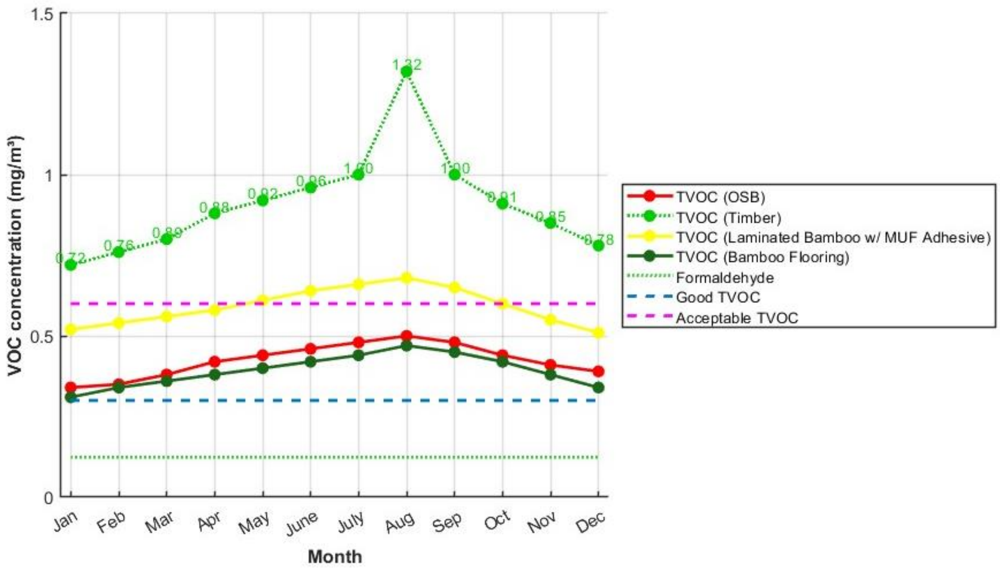

Fig. 18. VOC emissions under elevated temperatures, indicating a sharp increase in pollutant off-gassing from timber and MUF-bonded bamboo (Case Study 3.1)

However, VOC emissions exhibited clear temperature sensitivity. As illustrated in Figure 18, timber emissions peaked at 1.32 mg/m^3 in August, more than twice the peak level observed in Case Study 3.0. Likewise, laminated bamboo panels with MUF adhesive exceeded the acceptable limit, reaching 0.68 mg/m^3, while bamboo flooring saw increased emissions up to 0.47 mg/m^3 during the same month. These trends validate that VOC volatility intensifies with rising temperatures, as elevated heat accelerates off-gassing from building materials. While bamboo-based products remain environmentally promising, this case emphasizes that temperature conditions must be considered when evaluating long-term indoor air quality performance, particularly in thermally dynamic climates.

4.4.3 Case Study 3.2: Increased Ventilation Rate Scenario

In Case Study 3.2, the mechanical ventilation rate was elevated above baseline settings to evaluate the effectiveness of enhanced airflow in mitigating VOC concentrations. As shown on Fig. 19, the monthly average airflow exceeded 130 L/s during peak months and maintained higher values in cooler months, such as 87.34 L/s in November, compared to prior scenarios. This approach aimed to test whether dilution via airflow could offset emissions from high-VOC materials.

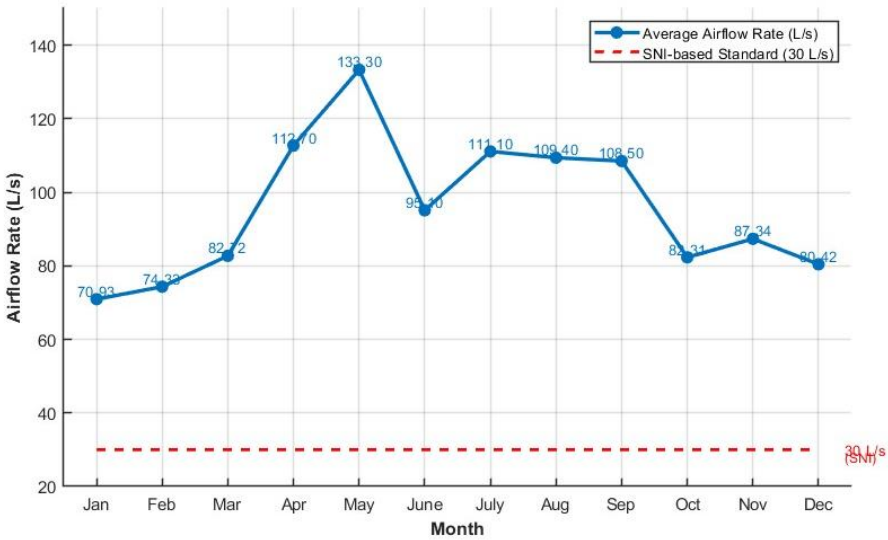

Fig. 19. Airflow patterns under enhanced ventilation conditions, demonstrating effective air dilution capacity in the system (Case Study 3.2)

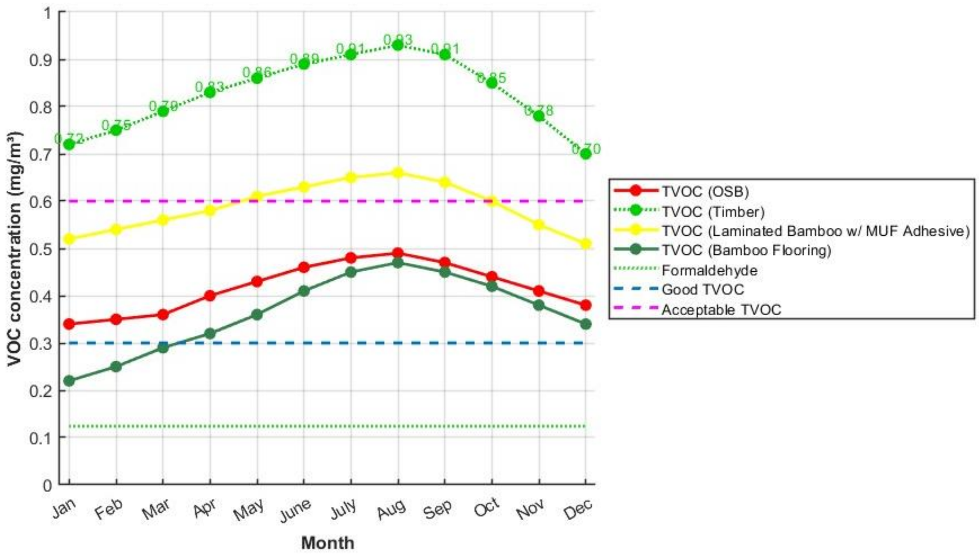

Fig. 20. VOC emission reduction achieved through increased mechanical ventilation, highlighting its effectiveness in pollutant dilution (Case Study 3.2)

The results, depicted on Fig. 20, indicate a measurable reduction in pollutant levels. Timber emissions dropped from a previous peak of 1.32 mg/m^3 (Case 3.1) to 0.93 mg/m^3, while bamboo flooring emissions decreased from 0.47 mg/m^3 to 0.34 mg/m^3 in December. Laminated bamboo with MUF adhesives also benefited, maintaining VOC concentrations near or just above the acceptable threshold throughout the year.

The simulation results across all nine case studies demonstrated that indoor air quality (IAQ) is highly sensitive to the choice of construction materials, adhesive types, and environmental conditions. In the baseline scenario (Case Study 1), the combination of OSB, gypsum, and cork flooring resulted in high indoor pollutant levels, with TVOC peaking at 3.775 mg/m^3 and formaldehyde at 1.25 mg/m^3, despite airflow rates exceeding the minimum SNI requirement. Removing cork in Case Study 1.1 improved IAQ, reducing TVOC to 2.33 mg/m^3 and formaldehyde to 0.52 mg/m^3. A detailed breakdown of these results is presented in Table 6, which compares the material configurations, emission peaks, airflow ranges, and overall IAQ performance for each case.

Significant improvements were observed in Case Studies 2.0 to 2.3, where laminated bamboo panels and bamboo flooring bonded with soy-based adhesives were introduced. These scenarios yielded the lowest emissions, especially in Case Study 2.1, where both cork and MUF adhesives were excluded—TVOC dropped to 1.10 mg/m^3, and formaldehyde was nearly undetectable. In contrast, Case Study 2.2, which used MUF adhesives, maintained acceptable but higher VOC levels, confirming that adhesive selection plays a key role in emission performance.

Environmental variables also influenced IAQ outcomes. In Case Study 3.1, increased indoor temperatures raised VOC emissions substantially, with timber TVOC reaching 1.32 mg/m^3. However, Case Study 3.2 showed that enhancing ventilation mitigated this effect, reducing TVOC to 0.93 mg/m^3, even when MUF adhesives were used. While the simulation framework focused on a single residential typology, the findings provide a generalized understanding applicable to similar urban housing typologies. Future extensions of this research could include multi-family units, school buildings, or commercial spaces to validate the material substitution strategy across broader building classes.

4.5 Comparison of Analytical and Simulated VOC Concentrations

The calculated analytical concentrations were then compared with the peak VOC values obtained from CONTAM for each case study. As shown in Table 7, while the analytical estimates were consistently lower in magnitude due to their idealized assumptions (e.g., perfect mixing), the relative trends closely matched the simulation outputs. High-emission cases (e.g., CS1 and CS1.1) yielded the highest VOC levels, while the bamboo-based systems (CS2.0–CS2.3) showed progressive reductions. Notably, Case Study 2.3, which employed full bamboo finishes with soy adhesives, achieved the lowest VOC values in both models. Additionally, environmental adjustments such as elevated temperature (CS3.1) and increased ventilation (CS3.2) reflected expected shifts in VOC behavior across both estimation methods.

The analytical values, while consistently lower in magnitude, exhibit the same relative trend as the simulation results. For instance, CS1, which employed high-emission materials such as OSB and cork, showed the highest values in both simulations (3.775 mg/m^3) and analytical estimates (0.154 mg/m^3). As lower-emission materials such as bamboo bonded with soy adhesives were introduced (CS2.0–CS2.3), the estimated VOC levels declined accordingly. Notably, CS2.3, which utilized full bamboo interior finishes, recorded the lowest simulated (0.88 mg/m^3) and analytical (0.026 mg/m^3) VOC concentrations.

Environmental variation scenarios further confirmed model reliability. In CS3.1, elevated temperature increased simulated VOC emissions (1.32 mg/m^3), mirrored by a higher analytical estimate (0.052 mg/m^3). Conversely, CS3.2 demonstrated the benefits of increased ventilation in reducing VOC levels, with both methods indicating decreased concentrations compared to CS3.1.

While absolute values differ due to idealized assumptions (e.g., perfect mixing), the directional agreement between the models validates the robustness of the CONTAM outputs. This consistency provides confidence in the simulation framework's capacity to predict indoor air quality trends resulting from material and environmental modifications. It also highlights the suitability of bamboo with bio-based adhesives in delivering lower indoor VOC concentrations under realistic operating conditions.

Table 6. Summary of simulation results for all case studies

Case Study	Key Material Configuration	Peak TVOC (mg/m^3)	Peak Formaldehyde (mg/m^3)	Airflow Range (L/s)	IAQ Performance Summary
Case Study 1	OSB + Gypsum + Cork	3.775	1.25	59.8 – 126.5	Exceeded VOC limits despite good airflow
Case Study 1.1	OSB + Gypsum (Cork Removed)	2.33	0.52	59.8 – 126.5	Improved IAQ, still above threshold
Case Study 2.0	Bamboo (Soy Adhesive) + Partial Cork	1.23	<0.3	59.8 – 126.5	Major VOC reduction
Case Study 2.1	Bamboo (Soy Adhesive) + No Cork	1.10	Near-zero	59.8 – 126.5	Optimal IAQ performance
Case Study 2.2	Bamboo (MUF Adhesive)	1.02	~0.45	59.8 – 126.5	Acceptable, but higher than soy adhesive
Case Study 2.3	Full Bamboo Panels + Flooring (Soy)	0.88	<0.3	59.8 – 126.5	Consistently low emissions
Case Study 3.0	Bamboo + MUF Adhesive (Standard Ventilation)	0.91	~0.5	70.8 – 138.3	Acceptable IAQ, moderate emissions
Case Study 3.1	Bamboo + MUF + High Temperature	1.32	0.68	70.8 – 133.3	VOCs exceeded safe range
Case Study 3.2	Bamboo + MUF + Increased Ventilation	0.93	0.45	87.3 – 138.3	Effective VOC reduction via dilution

Table 7. Analytical and Simulated VOC Concentrations Across Case Studies

Case Study	Material Configuration	Emission Rate E (mg/h)	Ventilation Rate Q (m^3/h)	Indoor Volume V (m^3)	Duration t (h)	Analytical VOC C(t) (mg/m^3)	Simulated Peak TVOC (mg/m^3)
CS1	OSB + Gypsum + Cork	70	455.4	518	8	0.154	3.775
CS1.1	OSB + Gypsum (No Cork)	45	455.4	518	8	0.099	2.330
CS2.0	Bamboo (Soy) + Partial Cork	25	455.4	518	8	0.055	1.230
CS2.1	Bamboo (Soy) + No Cork	15	455.4	518	8	0.033	1.100
CS2.2	Bamboo (MUF Adhesive)	20	455.4	518	8	0.044	1.020
CS2.3	Full Bamboo (Soy Adhesive)	12	455.4	518	8	0.026	0.880
CS3.0	Bamboo (MUF), Standard Ventilation	18	497.9	518	8	0.036	0.910
CS3.1	Bamboo (MUF), High Temperature	25	479.9	518	8	0.052	1.320
CS3.2	Bamboo (MUF), Increased Ventilation	18	497.9	518	8	0.036	0.930

5. Limitations of the Study

This study relied on simulation-based modelling using CONTAM to assess the impact of bamboo materials on indoor air quality, which, while powerful, involves assumptions that may not fully capture real-world conditions. Material emission factors, particularly for VOCs and formaldehyde, were sourced from literature and manufacturer data, which may not reflect variability due to product aging, production differences, or in-situ environmental interactions. Moreover, the adhesive formulations used in bamboo composites were modelled based on ideal chemical compositions, without accounting for on-site factors such as curing variability or application inconsistencies that could affect emission behaviour.

Additionally, the analysis was limited to a single residential building typology within a temperate climate zone, which may restrict the generalizability of the findings to other building types or climatic conditions. Dynamic occupant behaviours, window use, furniture interactions, and potential HVAC system faults were not included in the simulations, potentially underestimating variability in indoor air quality. Furthermore, the focus was placed solely on VOCs and formaldehyde, excluding other indoor pollutants such as particulate matter and biological agents, which also influence occupant health. Future studies should integrate experimental validation and a broader pollutant scope to support more holistic IAQ assessment.

In addition, this study did not incorporate dynamic occupant behavior such as window operation, furniture interaction, or variable HVAC performance, all of which can influence IAQ outcomes. While the simulation assumed uniform zone concentrations and consistent airflow paths (e.g., door gaps, diffusers), real-world variability could lead to more complex pollutant distributions. Furthermore, although bamboo emission values were based on published data, experimental validation under local environmental conditions would enhance future model accuracy.

6. Conclusion

This study presents a comprehensive simulation-based investigation into the indoor air quality (IAQ) implications of using bamboo-based materials in residential construction, with a particular focus on volatile organic compound (VOC) emissions. Through nine detailed case studies modelled using CONTAM software, the research evaluated the effects of various interior material combinations, adhesive types, thermal conditions, and mechanical ventilation rates. The results consistently demonstrate that the integration of engineered bamboo bonded with soy-based adhesives substantially improves IAQ, with total VOC (TVOC) and formaldehyde levels significantly lower than those of conventional materials like OSB and cork.

Key findings reveal that even with sufficient ventilation, high-emission materials can cause pollutant concentrations to exceed acceptable limits, highlighting the importance of source control in achieving healthy indoor environments. Substituting these materials with bamboo-based alternatives especially when paired with bio-based adhesives resulted in up to a threefold reduction in TVOC, with values falling below 1.0 mg/m^3 in optimal cases. Environmental conditions were found to strongly influence emission behaviour. Elevated indoor temperatures intensified VOC off-gassing, particularly from timber and MUF-bonded bamboo products, while increased mechanical ventilation provided a partial mitigation strategy through pollutant dilution. These findings underline that material substitution alone is not sufficient; rather, IAQ optimization must be approached holistically, combining low-emission materials with climate-sensitive ventilation strategies.

To validate the simulation findings, an analytical estimation using the well-mixed zone model was conducted. Although simplified in assumptions, the analytical results closely mirrored the trends observed in CONTAM outputs, supporting the reliability and predictive value of CONTAM software in early-stage IAQ assessments. The alignment of both approaches reinforces confidence in the modelling framework and confirms its suitability for guiding low-emission material selection during the architectural design process.

Beyond technical outcomes, this research offers several practical implications for architects, designers, and policymakers. First, the findings advocate for the specification of bamboo-based materials with soy-based adhesives in interior applications, especially in tropical and temperate climates. Second, given the influence of temperature and airflow, design strategies should integrate passive and active ventilation systems capable of responding to seasonal changes. Third, the framework can inform sustainable building codes and indoor air quality guidelines, promoting the adoption of bio-based materials in green certification systems.

Finally, although this study focused on a single residential building typology in a temperate proxy climate, the simulation approach is transferable to other building types, including schools, commercial spaces, and multi-family dwellings. Future research should extend this model to diverse climatic zones and incorporate experimental validations to further confirm emission behaviour under real-world conditions. Inclusion of economic analyses comparing bamboo-based systems with conventional materials would also enhance practical adoption. By demonstrating the material-environmental interplay in indoor pollutant control, this study contributes meaningful evidence to the growing discourse on health-centered, climate-resilient building design. It affirms that with appropriate material choices and system integration, sustainable construction can enhance both occupant health and environmental performance.

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