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Preliminary Study on the Emission Dynamics of TVOC and Formaldehyde in Homes with Eco-Friendly Materials: Beyond Green Building

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Abstract: This preliminary study investigates the emission characteristics of formaldehyde (HCHO) and total volatile organic compounds (TVOC) in indoor environments, comparing the effects of eco-friendly materials and general materials. The study analyzes the concentration changes over time in the living rooms of experimental units to assess the effectiveness of eco-friendly materials in reducing indoor air pollutants. The results show that eco-friendly materials exhibit lower initial emissions of TVOC than general materials, gradually decreasing over time. Compared to the eco-friendly material unit, the general material unit takes longer to reach acceptable TVOC concentrations. The emission pattern of HCHO differs from TVOC, with the highest peak occurring on the seventh day. Major individual VOCs, except for benzene, exhibit a similar decreasing trend for TVOC over time. Eco-friendly materials demonstrate significant reductions in emissions compared to general materials in various material applications, including parquet flooring, wallpaper, built-in furniture, and kitchen furniture. However, the difference in emissions for door and window frames using eco-friendly materials is minimal. These findings emphasize the effectiveness of eco-friendly materials in reducing indoor air pollutants and provide valuable insights for creating healthier living environments. Further research is needed to optimize the application of eco-friendly materials in specific components and investigate their long-term impact on indoor air quality and occupant health.

Keywords: indoor air quality (IAQ); eco-friendly materials; VOC emissions; HCHO emissions; Dubai

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1. Introduction

Recently, residential properties' insulation and airtightness requirements have become imperative for energy conservation [1]. Consequently, diverse construction techniques and the adoption of novel, high-efficiency, and multifunctional building interior materials have increased indoor air contaminants [2,3]. The building materials utilized in modern housing consist of intricate compounds and consequently release an array of perilous chemicals, including volatile organic compounds (VOCs) and formaldehyde (HCHO), which contribute to the degradation of indoor air quality (IAQ) [4,5]. Research is currently underway to investigate these emissions [6]. These harmful substances can potentially lead to various ailments among occupants, such as headaches, dizziness, nausea, drowsiness, and diminished concentration [7,8]. While not always directly or linearly correlated, these symptoms can collectively define sick building syndrome (SBS) [9]. Sick building syndrome (SBS) refers to non-specific health complaints often linked to exposure to indoor and outdoor air pollutants, including symptoms such as fatigue, headaches, irritations of the eyes, nose, and throat, dry cough, parched or itchy skin, dizziness, and difficulty maintaining concentration. The emission of hazardous chemicals indoors has given rise to numerous predicaments in the daily activities of inhabitants [10]. To address these issues, installing and operating appropriate ventilation systems is crucial, as is employing environmentally friendly materials while constructing new edifices and advancing the development of low-pollutant-emitting materials [11,12]. Desperate efforts are needed to tackle these challenges.

Various sources influence indoor air quality, each contributing to the presence of volatile organic compounds (VOCs) and formaldehyde (HCHO) in indoor environments. Construction materials, with their adhesives, sealants, and finishes, significantly release VOCs and HCHO indoors. However, they are not alone in this; furniture and furnishings made of composite wood products, household products such as cleaning agents, and even personal care items can emit these pollutants. Moreover, cooking and heating appliances, particularly gas stoves, can introduce combustion byproducts, including VOCs, into indoor air [13]. Outdoor sources such as traffic emissions and industrial activities can infiltrate indoor spaces, while human activities such as smoking and hobbies involving solvents add to the mix. Outdoor air quality also influences indoor air quality, and effective ventilation can help dilute pollutants and mitigate their impact. Managing indoor air quality effectively necessitates a holistic approach that addresses these diverse sources and employs strategies such as source control, ventilation, and air purification to ensure healthier indoor environments [14].

Extensive research conducted in Dubai has highlighted the critical nature of indoor air quality (IAQ) and its profound impact on residents [15,16]. Kim et al. (2022) conducted a study in Dubai, revealing that 15% of the city's population has reported experiencing symptoms associated with sick building syndrome (SBS). This syndrome is characterized by various non-specific health complaints often linked to exposure to a complex mix of indoor and outdoor air pollutants [17]. SBS is a multifaceted issue highlighting the importance of indoor air quality in urban settings, where individuals spend a significant portion of their lives in various environments. Understanding the factors contributing to SBS, including specific pollutant sources, ventilation systems, and building design, is crucial for promoting healthier indoor environments and the well-being of urban populations. The symptoms of SBS include fatigue, headaches, irritations of the eyes, nose, and throat, dry cough, parched or itchy skin, dizziness, and difficulty maintaining concentration. To recognize these concerns and ensure compliance with IAQ standards, the Dubai Municipality has outlined specific concentration thresholds [18]. These mandates stipulate that HCHO levels should not exceed 0.08 parts per million (ppm), total volatile organic compounds (TVOC) should be maintained below 300 $\mu g/m^3$, and particulate matter (PM_{10}) should be limited to 150 $\mu g/m^3$. These measurements are obtained through continuous monitoring over 8 h before newly constructed houses are occupied [19].

Arar et al. (2022) surveyed between December 2021 and January 2022, targeting residents of townhouses in Dubai, and revealed a notable level of awareness regarding SBS [20]. A significant 95% of respondents indicated having above-average knowledge of SBS [21]. However, despite this awareness, a majority demonstrated limited knowledge or indifference towards methods to improve IAQ [22]. It was observed that individuals who spent substantial amounts of time indoors, such as housewives and children, were the most adversely affected [23]. Furthermore, Carrer and Wolkoff (2018) identified a trend of increased vigilance among individuals in assessing IAQ before relocating [24]. However, once settled, there was a lack of guidance and systems for maintaining healthy living conditions [25].

Regarding construction practices, most developers in Dubai have adopted eco-friendly materials, established ventilation systems, and implemented pre-occupancy bake-outs to ensure compliance with recommended indoor air quality standards in new apartment buildings [26]. However, after moving in, residents are responsible for actively enhancing the indoor air environment [27]. This can be achieved through diligent utilization of ventilation facilities and restricting the use of household items that contribute to indoor pollutant generation, thereby reducing pollutant concentrations [28].

Jung et al. (2021) focus on evaluating the indoor environment within specific developments, such as The Springs, an iconic townhouse-type residential complex in Dubai [29]. This research aims to discern residents' preferences concerning various indoor environmental factors, including thermal comfort, indoor air quality, lighting, and acoustics [30]. Preliminary findings indicate that, during the summer, thermal comfort emerges as the foremost concern for living rooms and master bedrooms. In contrast, indoor air quality assumes greater significance during winter [31,32]. The outcomes of this research are expected to guide future renovation guidelines to enhance indoor environments, particularly in buildings nearing the twenty-year mark, thereby preventing complications associated with SBS [33].

Furthermore, to enhance the quality of final interior finishing materials, utilizing substances that possess diminished levels of hazardous chemicals is also necessary [34]. Additionally, there is a growing need to systematically evaluate the efficacy of employing these materials [35].

This research employs a meticulous selection process to identify eco-friendly and conventional materials as primary candidates for indoor finishing materials, known to be the primary culprits behind indoor air pollution [36]. Subsequently, experiments are conducted to examine the emission of harmful chemicals and assess the effectiveness of implementing eco-friendly building materials [37]. The specific objectives encompass two principal aims: firstly, to evaluate the performance of experimental houses constructed using both eco-friendly materials and conventional materials [38]; secondly, to ascertain the emission characteristics of HCHO and VOCs within the living spaces, accounting for the location of each construction material [39,40].

2. Materials and Methods

2.1. Research Methods and Procedures

As shown in Table 1, four mockup test units, labeled 4A, 6B, 8C, and 10D, were meticulously constructed at the Sobha Hartland One Park Avenue construction site before the completion of the apartment [41].

Table 1. Composition of the four experimental units.

Sobha Hartland One Park Avenue	Experiment Contents		
	Material	Duration	Evaluation Criteria
Unit 4A	General material	81 days	Concentration changes over time
Unit 6B	Eco-friendly material		
Unit 8C	General material	14 days for each material	Changes in indoor pollutant concentration according to the construction location for each material
Unit 10D	Eco-friendly material		

Experimental unit 4A was erected using conventional materials, while experimental unit 6B employed eco-friendly materials, enabling the assessment of long-term reductions in HCHO and VOCs (Figure 1) [42,43]. Furthermore, experimental units 8C and 10D were dedicated to general and eco-friendly materials [44]. Sequentially, these units involved the installation of wallpaper (including adhesive), floor materials (including adhesive), general furniture, kitchen furniture, and wooden window and door materials at approximately two-week intervals [45]. The concentrations of formaldehyde and VOCs were measured on the first day and the fifth to eighth days after each construction phase, employing a repetitive construction cycle, measurement, and demolition [46].

To elaborate, the wallpaper experiment commenced with an initial measurement of background concentration, followed by the installation of wallpaper on the walls and ceiling of the living room, each room, and the kitchen in the experimental units [47]. The emissions were monitored and recorded before material removal [48]. Upon removal, thorough ventilation was conducted by fully opening the doors of all units for a specific duration [49]. Subsequently, the background concentration was remeasured before proceeding with the construction of subsequent materials [50].

Figure 1. Unit 6B in Sobha Hartland One Park Avenue. Measurement point: Grey Wolf device.

The order of construction materials was determined based on the ease of dismantling and minimal residual impact [51]. General furniture, kitchen furniture, wooden windows, wallpaper, and flooring materials were successively installed [52]. Moreover, when calculating the final concentration, the background concentration measured before construction was subtracted and considered [53].

In this study, eco-friendly materials encompass substances specifically developed to reduce hazardous chemicals compared to conventional materials [54]. Table 2 provides detailed information regarding their specific composition.

Table 2. Comparison of the composition of finishing materials.

Classification			General Material	Eco-Friendly Material
Wallpaper (adhesive)			PVC-based wallpaper (general adhesive)	PP-based wallpaper (HCHO low-emission adhesive)
Parquet flooring (adhesive)			General flooring (Oil-based epoxy adhesive)	Hazardous chemical substance reduction floor (Urethane adhesive)
Window frame	Core material		Laminated wood E2 grade	Laminated wood E1 grade
	Surface material		HDF E2 grade LVL E2 grade	HDF E1 grade LVL E1 grade
Built-in Furniture	Core material	Body frame	PB E2 grade	PB E1 grade
		Door	MDF E2 grade	MDF E1 grade
	Surface material		PVC wrapping	LPM
Kitchen furniture	Core material	Body frame	PB E2 grade	PB E1 grade
		Door	MDF E2 grade	MDF E1 grade
	Surface material		Laquer paint	UV paint

Wallpaper was affixed to the walls and ceiling of the living room, as well as the walls and ceiling of each of the three individual rooms and the kitchen [55]. Conventional materials employed polyvinyl chloride (PVC)-based resin for the wallpaper, while eco-friendly materials employed polypropylene (PP)-based resin [56]. Flooring materials were installed in the living room and kitchen. Conventional floorboards utilized oil-based epoxy resin-based adhesives, whereas eco-friendly floorboards utilized urethane resin-based adhesives [52,57].

General furniture includes a shoe rack, a dressing table in the master bedroom, a closet in the dressing room, and a decorative cabinet in the living room [58]. Regarding the materials utilized for general furniture, the core body employed a particle board (PB), while the doors were constructed using medium density fiberboard (MDF) [59]. It is worth noting that these furniture materials adhered to the E2 grade for HCHO emissions, ensuring limited radiation of HCHO [60]. Conversely, eco-friendly furniture materials adhered to the E1 grade, signifying a higher level of environmental friendliness [61]. Regarding surface treatment, adhesives were circumvented using the PVC wrapping technique for general furniture materials [62]. On the other hand, the low-pressure laminate (LPM) processing method was employed for eco-friendly furniture materials [63].

The kitchen area was furnished with general furniture comprising a core body of PB E2-grade and MDF E2-grade materials to ensure compliance with the specified formaldehyde (HCHO) radiation standards [64]. Furthermore, a membrane finish was applied for a polished appearance [65]. On the other hand, eco-friendly kitchen furniture featured PB E1-grade and MDF E1-grade materials and a coating of ultraviolet curing (UV) paint, signifying a commitment to environmentally conscious practices [66].

Wood windows and doors encompass the materials utilized for each room's doors, doorframes, and window frames. The core component of general and eco-friendly materials comprises E2-grade laminated wood and a high-intensity fiberboard (HDF) surface layer. In the case of general materials, veneer lumber (LVL) adhered to the E2 grade, while HDF met the E1 grade requirements. Eco-friendly materials, on the other hand, adhered to E2 grade specifications. The experiment entailed a repetitive process of constructing and demolishing the aforementioned materials in each designated area, carried out sequentially.

2.2. Target Building Status

The focus of measurement encompassed the two-bedroom units (102.13 m^2) within the Sobha Hartland One Park Avenue apartment complex situated in Mohammad Bin Rashid Al Maktoum City (MBR), Dubai [67]. The experiment was conducted over the period spanning from November 2022 to December 2022. The room conditions were diligently maintained during the experiment at an air temperature of 25 °C. Figure 2 illustrates the experimental layout, showcasing the plan view and the positioning of the measuring points.

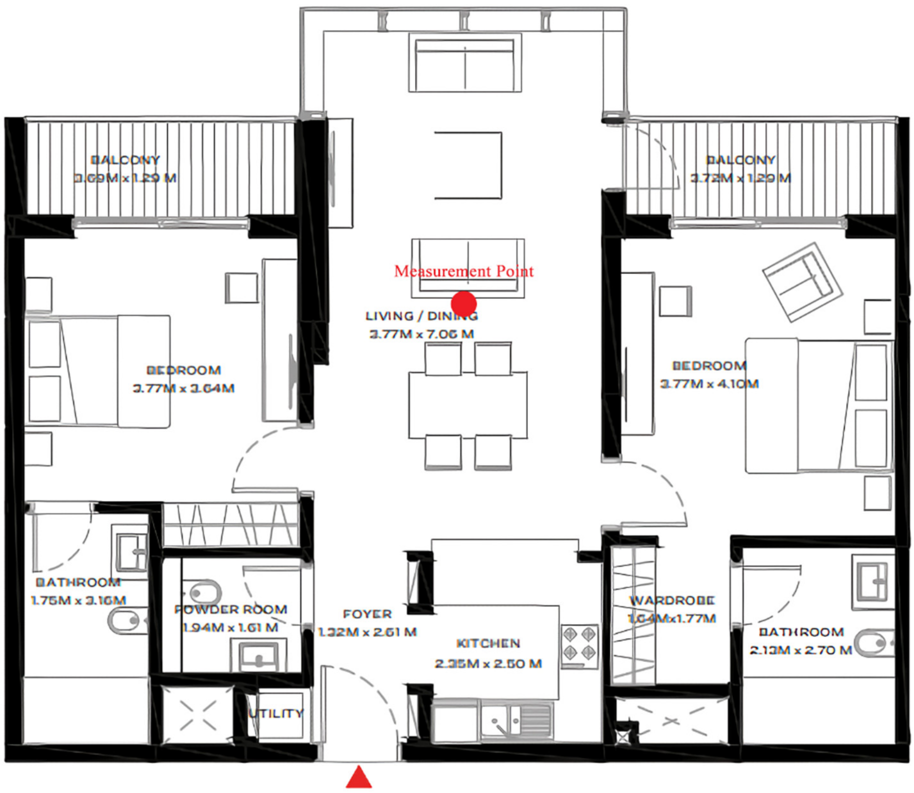

Figure 2. Measurement point.

The measurement locations were determined based on the living room, serving as the primary measurement point [68]. Each material was measured at its main construction location (e.g., bedroom, kitchen). To clarify further, the living rooms of units 4A and 6B were measured. In contrast, in units 8C and 10D, the living rooms were assessed for flooring, wallpaper, general furniture, and wooden window and door installations. In contrast, the living rooms and bedrooms were examined for kitchen furniture.

The measurement points were positioned at the center, with a minimum distance of 1 m from the walls, and the height was set between 1.2 and 1.5 m from the floor [69]. Indoor air collection was measured following a process adhering to the World Health Organization's (WHO) IAQ testing method [70]. This entailed 30 min of ventilation followed by 5 h of sealing. The concentration of VOCs emitted by each building material was calculated by determining the concentration of individual VOCs and compounds identified through analysis. For compounds that could not be specifically identified, they were converted to the concentration of toluene, and subsequently, the concentration of TVOC was calculated by summing the two concentrations.

2.3. Measurements

Specialized measurement sensors were employed to collect data on indoor air quality meticulously. These sensors were thoughtfully selected based on their exceptional accuracy and reliability in quantifying the concentrations of formaldehyde (HCHO) and volatile organic compounds (VOCs) in the indoor environment.

A highly sensitive approach was adopted for VOC measurements, utilizing a stainless tube filled with 200 mg of Tenex-TA (60/80 mesh, Supelco, Bellefonte, PA, USA) for solid adsorption. Similarly, for HCHO measurements, we employed a purified 2,4-DNPH Silica Cartridge (Supelco, S10, Bellefonte, PA, USA). To maintain the utmost precision in our measurements, a micro pump (Gilian, Pinellas County, FL, USA) was meticulously chosen for its minimal flow fluctuations before and after measurements, guaranteeing our data's accuracy and reliability. The flow rates for VOC and HCHO measurements were set at 50 mL/min and 250 mL/min, respectively. These flow rates were continually monitored using a digital flow meter (All-tech, Lexington, KY, USA), ensuring that fluctuations remained within the 5% range.

Our analytical arsenal was further bolstered by utilizing gas chromatography with mass spectrometry detection (GC/MSD) for VOC analysis. This state-of-the-art approach incorporated an HP-1 Capillary column (60 m $\times$ 0.32 mm $\times$ 5 μm) and adhered to rigorous analysis conditions. These conditions entailed maintaining the column temperature between 40 °C and 220 °C, maintaining a column flow rate of 1 mL/min, and sustaining a mass spectrometry detector (MSD) temperature of 230 °C.

HCHO analysis was performed using high-performance liquid chromatography (HPLC) with a C-18 column (3.9 $\times$ 300 mm) to ensure comprehensive analysis. The mobile phase consisted of acetonitrile and water in a precise ratio of 55:45, with detection conducted at a wavelength of 360 nm. The flow rate was methodically set at 1.0 mL/min, and each sample was injected using a consistent volume of 20 μL. The acetonitrile and water used in the analysis were procured from reputable suppliers to meet the highest analytical standards. These measurement sensors and analytical methods were thoughtfully selected for their exceptional precision and reliability, underscoring our unwavering commitment to ensuring the utmost accuracy in our data collection process.

2.4. Sample Collection and Analysis Method

The solid adsorption method used a stainless tube filled with 200 mg of Tenex-TA (60/80 mesh, Supelco, Bellefonte, PA, USA) to measure VOCs. For HCHO measurements, a purified 2,4-DNPH silica cartridge (Supelco, S10, Bellefonte, PA, USA) was utilized. A micro pump (Gilian, Pinellas County, FL, USA) with minimal flow fluctuations before and after measurements was utilized for VOC and HCHO measurements.

In the case of VOCs, a total volume of 1.5 L was measured over 30 min, with a flow rate of 50 mL/min. For HCHO measurements, a total volume of 7.5 L was measured over the same 30 min period at a flow rate of 250 mL/min. The flow rate before and after the measurement was assessed using a digital flow meter (Alltech, Lexington, KY, USA), ensuring that the variation in flow rate remained within 5%.

Before measurement, VOCs were thermally desorbed and conditioned using ATD-400 (Perkinelmer, Buckinghamshire, UK). After measurement, the VOC adsorption tube was securely sealed, protected from light, and stored in a cool and dark environment at temperatures below 4 °C until further analysis. The desorbed VOCs from the adsorption tube were separated using a BP-1 column as the stationary phase and detected using a mass spectrometry detector (MSD) (PerkinElmer, Buckinghamshire, UK). The following are the analysis conditions for GC/MSD (Table 3).

Table 3. Conditions for VOC analysis.

Equipment	Analysis Conditions
GC/MSD	HP 6890/HP-5973N Column: HP-1 Capillary column(60 m × 0.32 mm × 5 μm) Column temperature: 40 °C (5 min) >> 70 °C (5 min) >> 150 °C (5 min) >> 200 °C (5 min)->220 °C (5 min) Ramp rate: 5 °C/min to 200 °C, 10 °C/min to 220 °C Column flow: 1 mL/min MS ion source temp: 230 °C

During the measurement of HCHO, certain factors, such as ozone, sunlight, and moisture, can interfere with the derivatization reaction of aldehydes. To mitigate the impact of ozone, an ozone scrubber (Waters, Milford, MA, USA) was employed at the front end of the 2,4-DNPH cartridge. Additionally, the influence of sunlight was deemed negligible, as it did not directly affect the measurement point. Following the measurement, the sample was carefully sealed, shielded from light using aluminum foil, and stored in a cool, dark environment below 4 °C. The sample was then fixed within a sample extractor, namely, the Vacuum Elution Rack (Supelco, Bellefonte, PA, USA), and filtered using an oil-soluble filter (47 mm diameter, 0.45 μm pore size, PTFE), employing HPLC-grade acetonitrile (JTbaker, Phillipsburg, NJ, USA) solution. A volume of 5 mL was extracted for analysis. Sample analysis was conducted using high-performance liquid chromatography (HPLC). The following outlines the analysis conditions for HCHO (Table 4).

Table 4. Conditions for HCHO analysis.

Equipment	Analysis Conditions
HPLC	Column: C-18 column (3.9 × 300 mm) waters U.S.A. Mobile phase: acetonitrile/water = 55:45 UV detector: 360 nm Flow rate: 1.0 mL/min Sample injection amount: 20 μL

3. Results

3.1. Comparison of VOC and HCHO Emission Concentrations over Time between General and Eco-Friendly Material

The findings of this experiment elucidate the concentration changes over time in the living rooms of experimental units 4A and 6B. Figures 3 and 4 present the long-term variations in TVOC and HCHO concentrations for both the eco-friendly and general material units.

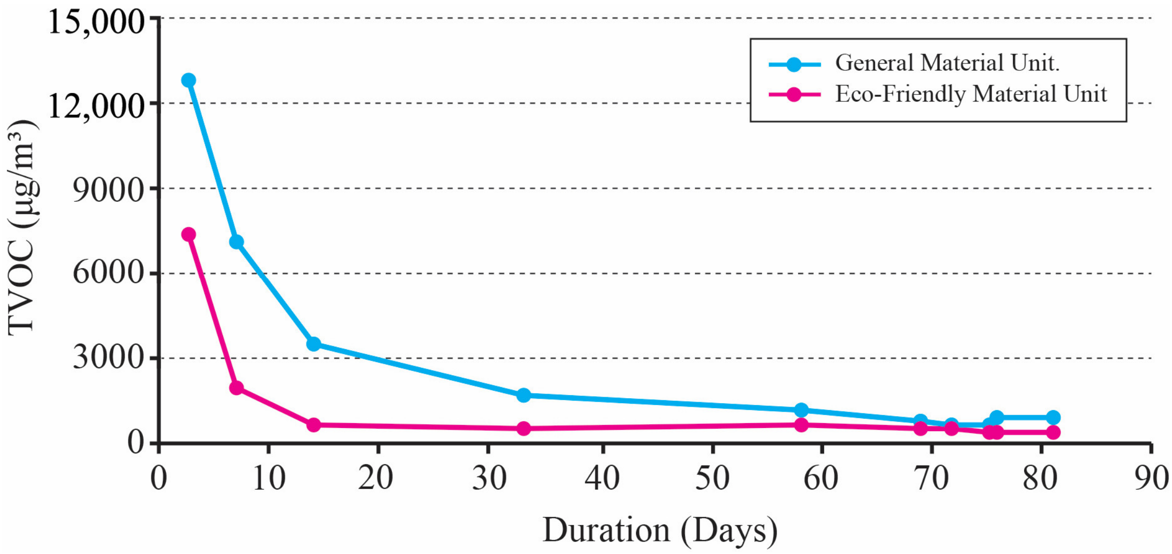

Figure 3. The concentration of TVOC in the general material unit and the eco-friendly unit.

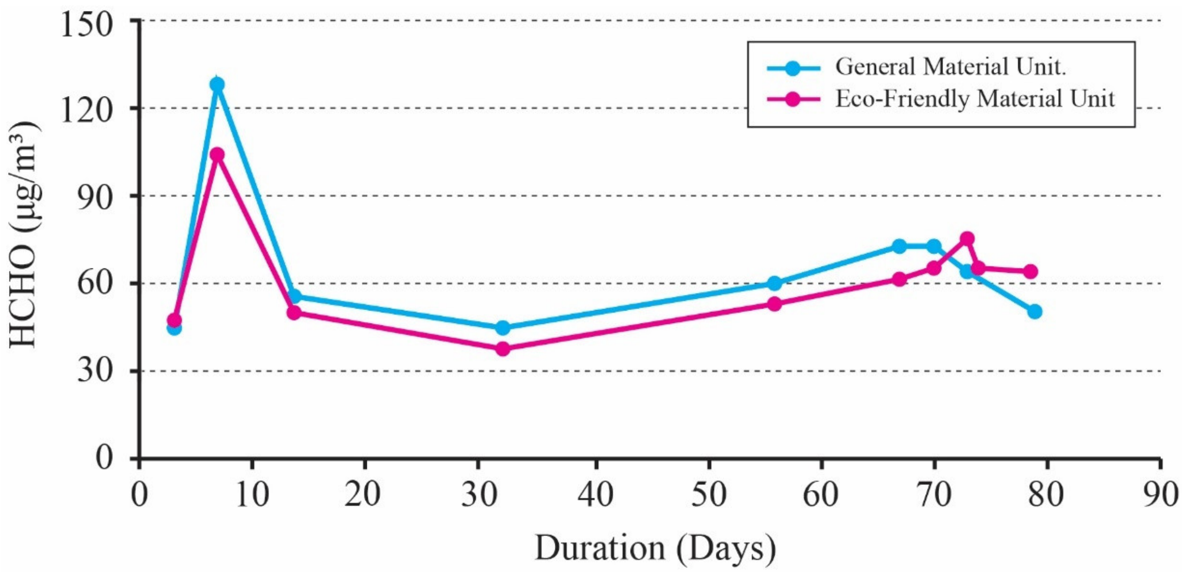

Figure 4. The concentration of HCHO in the general material unit and the eco-friendly unit.

The initial TVOC concentration in the general material unit was approximately 1.7 times higher than in the eco-friendly material unit. However, it exhibited a decreasing trend over time, indicating a high initial emission of pollutants that gradually diminished. Conversely, in the eco-friendly material unit, the TVOC concentration dropped below 1000 $\mu g/m^3$ after 14 days of construction and remained stable even after several tens of days.

In contrast, it took 69 days of construction for the concentration of the general material unit to fall below 1000 $\mu g/m^3$. The TVOC concentration in the general material unit was consistently lower than in the eco-friendly material unit, but it required more than 50 days to achieve such levels. Figure 3 illustrates a similar trend in TVOC emission concentration between the general and eco-friendly material units after several construction days have elapsed. Considering these observations, the application of eco-friendly materials proves effective in ensuring a more comfortable indoor air quality for residents when moving in, especially considering the typical occupancy timeline of 30 days after the completion of interior finishing materials.

Unlike TVOC, the maximum peak of HCHO emission concentration occurred on the seventh day, reaching 126 $\mu g/m^3$ in the general material unit. It is important to note that

HCHO concentrations may exhibit fluctuations depending on indoor temperature and humidity conditions. However, in this experimental setting, temperature fluctuations were minimal due to the consistent indoor temperature of 23 ± 1 °C maintained throughout the experiment (Figure 4). Nevertheless, it is worth mentioning that although the room temperature controller in the living room was set at 25 °C, the measured air temperature in the central breathing area of the living room was approximately 2 °C lower.

Upon analyzing the temporal variations in indoor concentrations of major individual volatile organic compounds (VOCs), it was observed that most substances exhibit a similar declining trend as that of the total volatile organic compounds (TVOC) (Figures 5–9). Notably, toluene has substantial emission levels and a decreasing pattern that is remarkably comparable to TVOC (Figure 6). However, benzene showcases a distinct behavior with low initial emission levels, displaying a cyclic pattern of fluctuations over time. In all cases, except for benzene, the initial emission levels (60 days before the start of the experiment) are considerably higher in general materials compared to eco-friendly materials, indicating a significant disparity. Therefore, eco-friendly materials are effective in mitigating initial emissions [53].

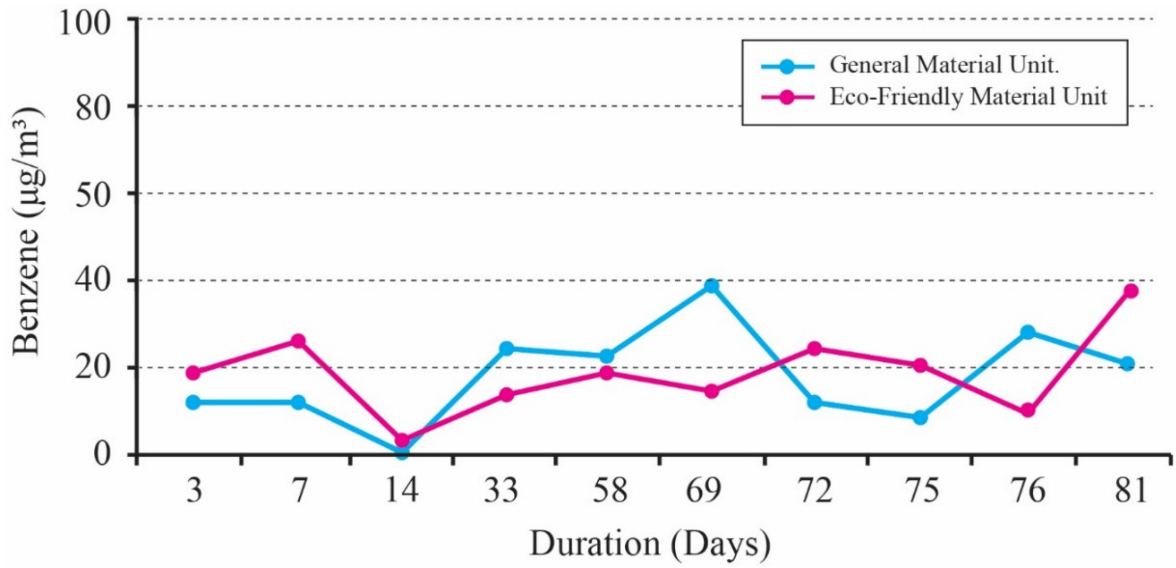

Figure 5. The concentration of benzene in the general material unit and the eco-friendly unit.

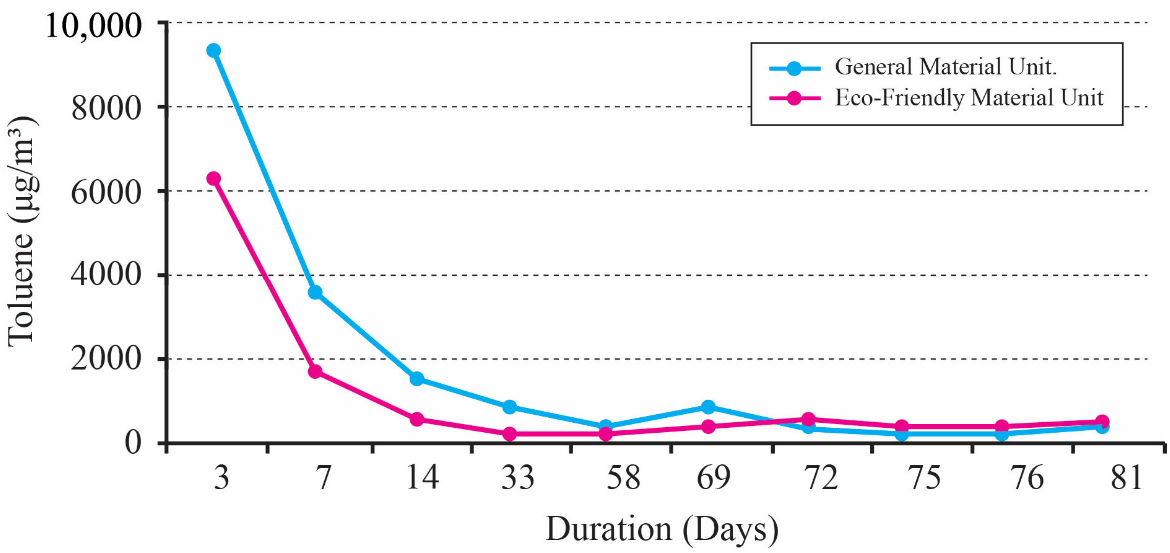

Figure 6. The concentration of toluene in the general material unit and the eco-friendly unit.

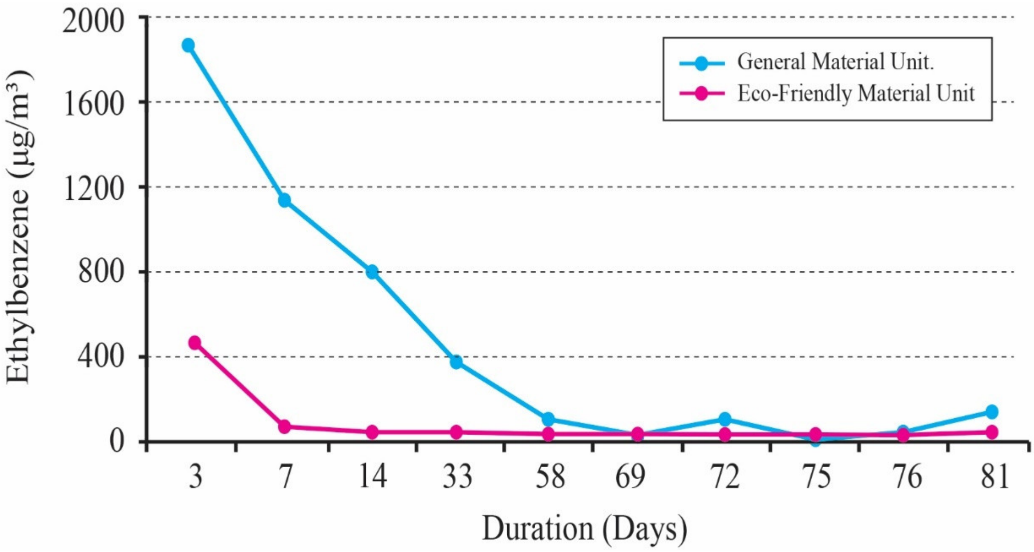

Figure 7. The concentration of ethylbenzene in the general material unit and the eco-friendly unit.

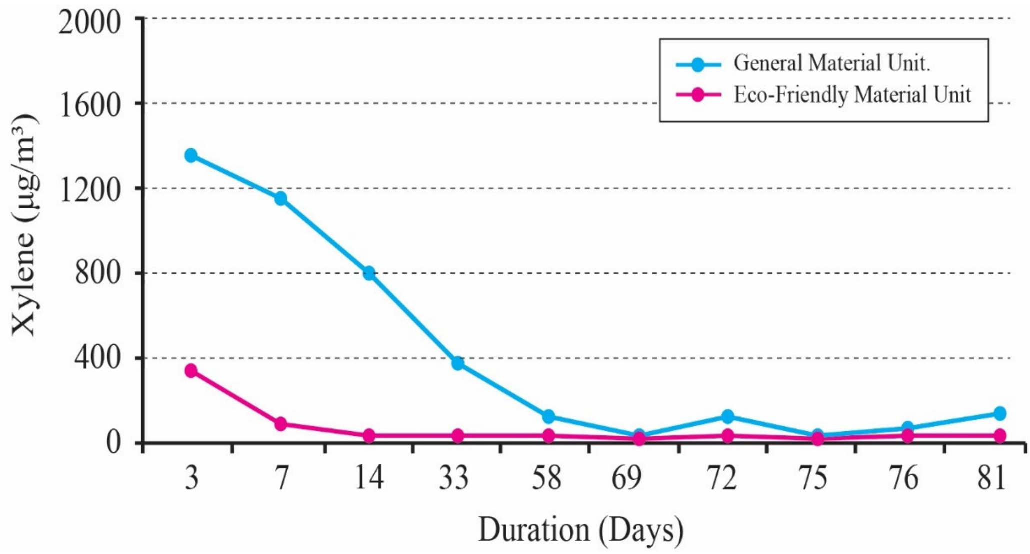

Figure 8. The concentration of xylene in the general material unit and the eco-friendly unit.

3.2. Comparison of TVOC and HCHO Emission Concentrations by Locations between General and Eco-Friendly Material

The outcomes of this study pertain to the experimental units 8C and 10D. The experiment aimed to ascertain the emission characteristics of HCHO and VOCs indoors concerning the construction location of each material. Furthermore, the efficacy of eco-friendly materials for each specific material was evaluated. Measurements were conducted at the central position within the living room area.

3.2.1. Parquet Flooring

Parquet flooring was meticulously installed in both the living room and kitchen areas. An adhesive containing oil-based epoxy resin was utilized for conventional flooring materials, while eco-friendly flooring materials employed a resin adhesive based on urethane. A comparative analysis of TVOC emissions reveals a substantial disparity. The construction of eco-friendly flooring materials results in significantly lower emission levels compared to the installation of conventional floor materials (Figure 10).

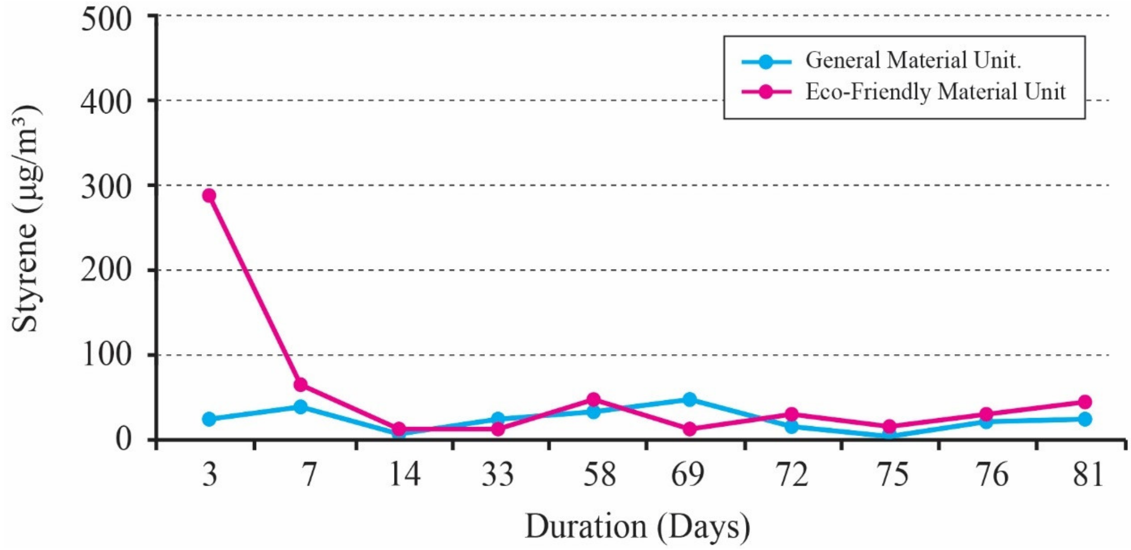

Figure 9. The concentration of styrene in the general material unit and the eco-friendly unit.

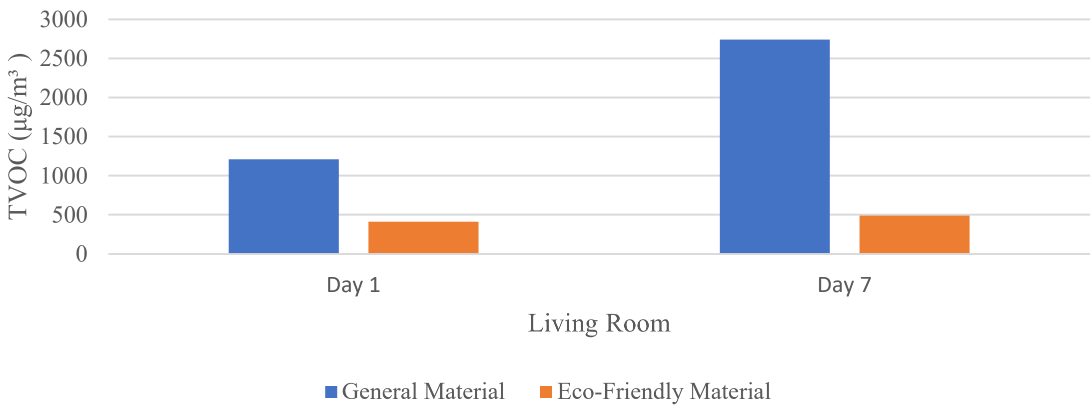

Figure 10. TVOC concentration according to the parquet flooring.

Regarding HCHO emissions, eco-friendly flooring materials exhibit lower overall levels than general flooring materials. Specifically, on the first day after construction, the difference in emissions was approximately twice as large. However, it should be noted that there was a slight increase in emission amounts over time, and the disparity with the emission levels of general flooring materials was not significantly large (Figure 11).

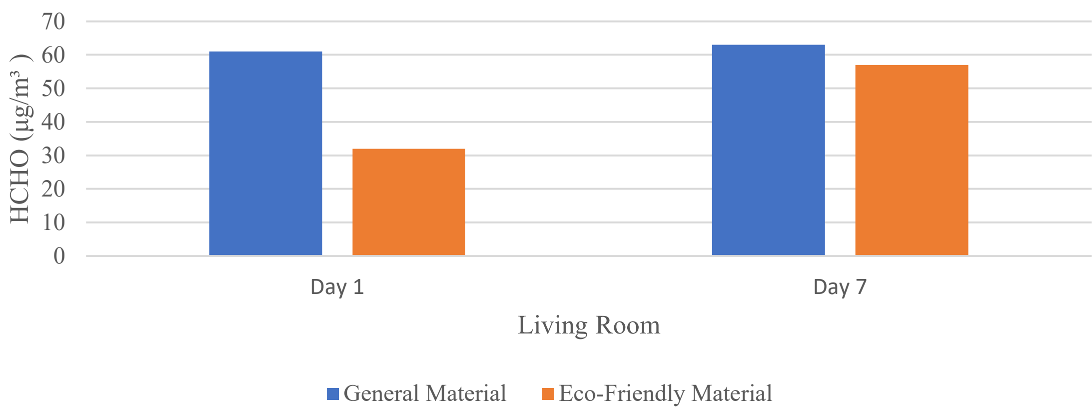

Figure 11. HCHO concentration according to the parquet flooring.

3.2.2. Wallpaper

The experiment focused on two types of wallpaper: one made with PVC (polyvinyl chloride) resin and the other made with PP (polypropylene) resin. The experiment results demonstrated a reduction in the emissions of TVOC and HCHO with the use of eco-friendly wallpaper (Figure 12). Specifically, on the first day after construction, a considerable concentration of emissions was observed, highlighting the notable difference between eco-friendly wallpaper and general wallpaper. By the sixth day, there was no significant emission level disparity between the general and eco-friendly wallpaper. However, it was evident that the emission amounts were significantly reduced compared to the first day, indicating the effectiveness of eco-friendly wallpaper in minimizing emissions over time (Figure 13).

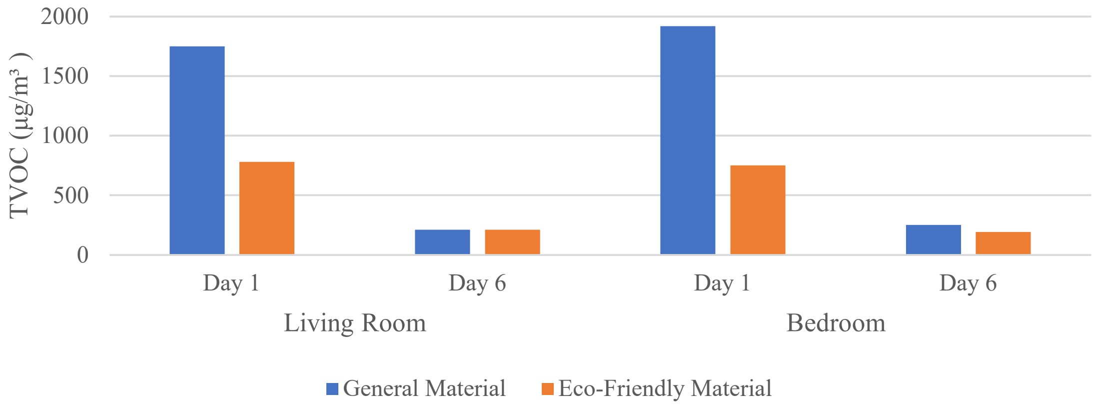

Figure 12. TVOC concentration according to the wallpaper.

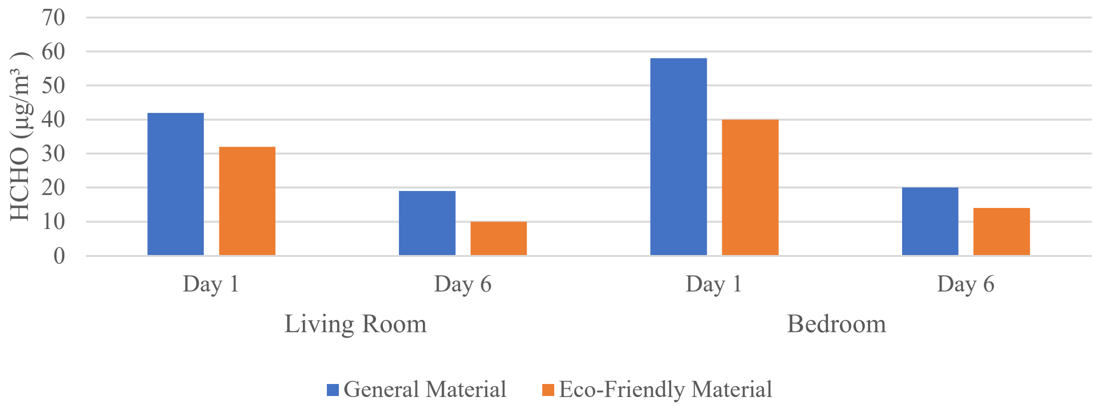

Figure 13. HCHO concentration according to the wallpaper.

3.2.3. Built-in Furniture

The emission levels were measured on the first and seventh days after installing general furniture in the experimental household, including shoe cabinets, dressing tables in the master bedroom, closets in the dressing room, and cabinets in the living room. Figures 14 and 15 illustrate the concentrations of TVOC in the living room and bedroom after general furniture and eco-friendly materials are installed. In the case of general furniture, it was observed that eco-friendly materials resulted in a significant reduction in TVOC concentrations. Regarding HCHO emissions, it was noted that on the first day in the bedroom, eco-friendly furniture exhibited slightly higher emissions than general furniture. However, after seven days of construction, it was confirmed that the emission levels were more than twice as low when using eco-friendly materials compared to general materials.

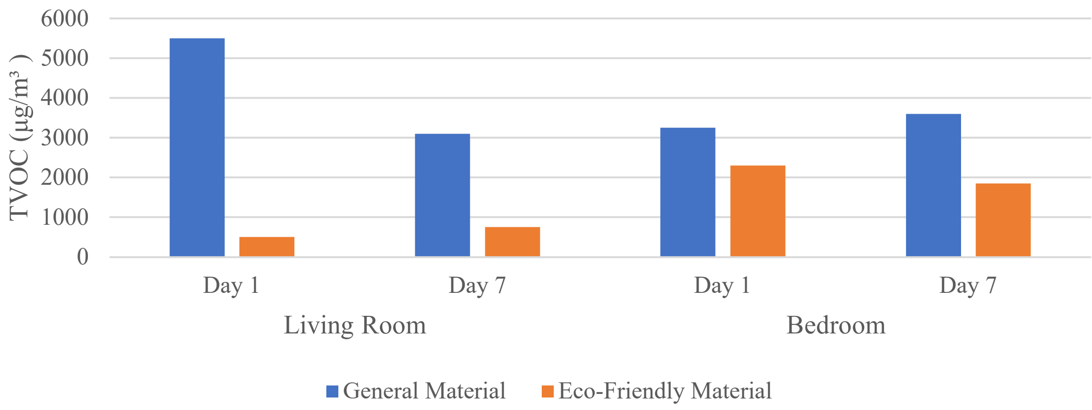

Figure 14. TVOC concentration according to the built-in furniture.

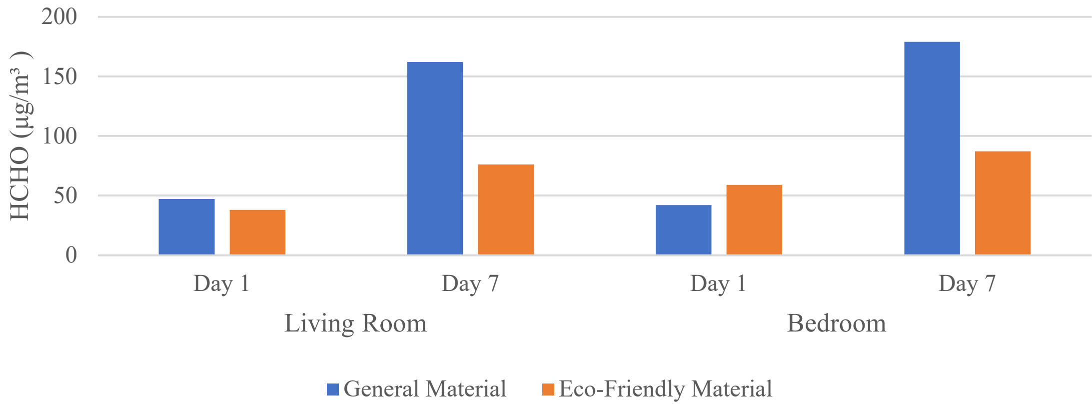

Figure 15. HCHO concentration according to the built-in furniture.

3.2.4. Kitchen Furniture

When considering kitchen furniture, eco-friendly subsidiary materials resulted in a more than two times reduction in TVOC emissions compared to general subsidiary materials (Figure 16). This reduction was observed at the beginning of construction and on the eighth day. In the case of eco-friendly kitchen furniture, the application of UV paint as the surface finish played a significant role in reducing VOC emissions. The paint-drying process during the molding stage contributed to lower VOC emissions after the furniture was installed in the experimental unit. Using eco-friendly subsidiary materials led to lower HCHO emissions than general subsidiary materials (Figure 17).

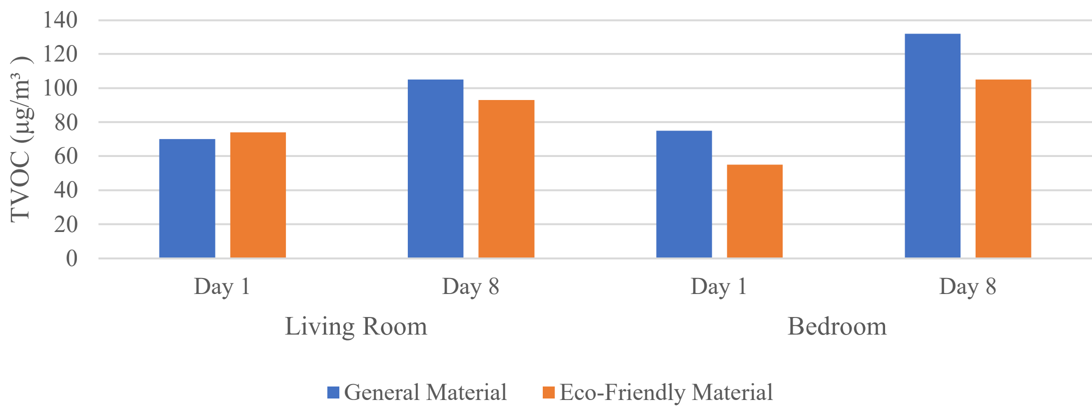

Figure 16. TVOC concentration according to the kitchen furniture.

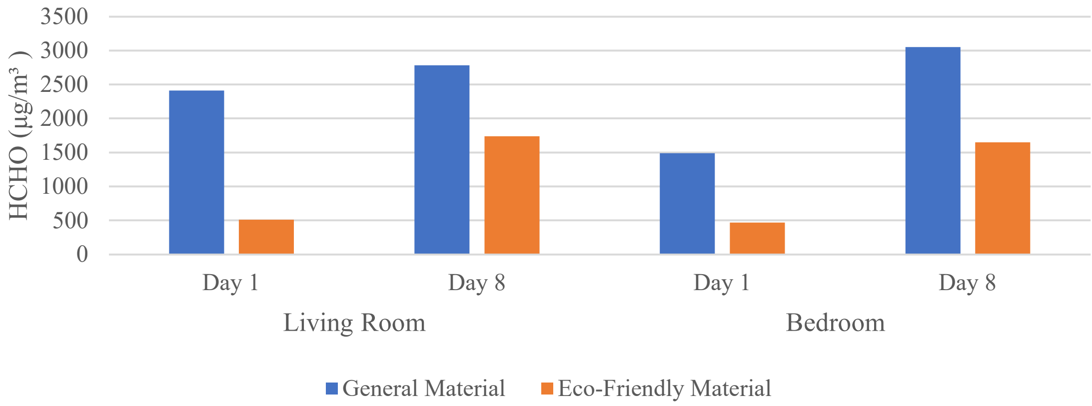

Figure 17. HCHO concentration according to the kitchen furniture.

3.2.5. Door/Window Frame

Regarding door and window frames, E2-grade laminated wood, HDF, and LVL were used with general auxiliary materials. In contrast, eco-friendly auxiliary materials were assigned an E1 grade to enhance performance. As a result, both TVOC and HCHO emissions were slightly lower when eco-friendly subsidiary materials were utilized. However, the difference in emissions was minimal, indicating the need for further emphasis on applying eco-friendly materials for wooden windows and doors (Figures 18 and 19).

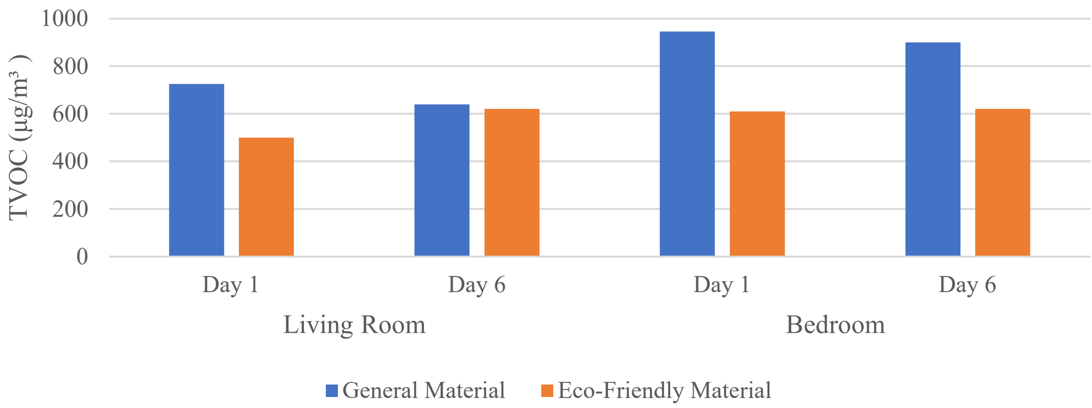

Figure 18. TVOC concentration according to the door/window frame.

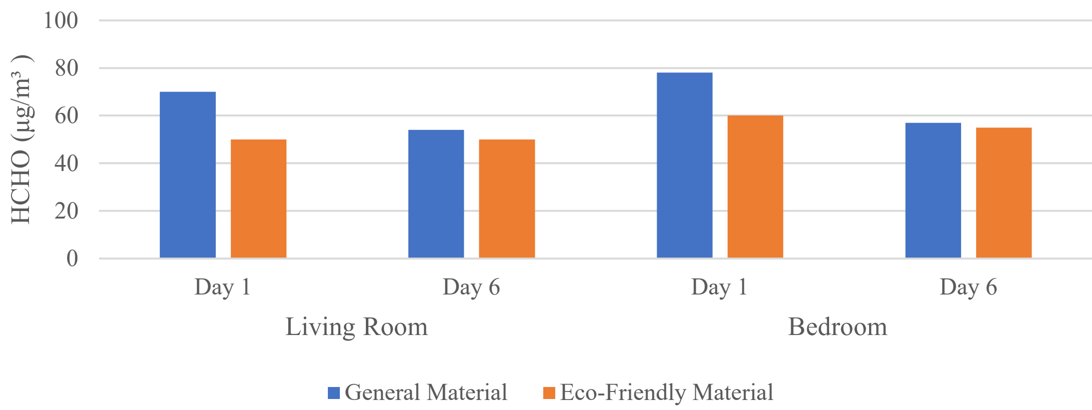

Figure 19. HCHO concentration according to the door/window frame.

4. Discussion

The findings of our experiment yield valuable insights into the emission characteristics of VOCs and HCHO in indoor environments, comparing the effects of general materials and eco-friendly materials. The temporal changes in concentrations within the living rooms of the experimental units serve as evidence of the efficacy of eco-friendly materials in reducing indoor air pollutants.

Our findings indicate that the initial concentration of TVOC in the general material unit was approximately 1.7 times higher than that in the eco-friendly material unit. However, the TVOC concentration in the general material unit gradually decreased over time. It's important to note that this reduction reflects the concentration levels, not necessarily the emission rate, which could also be influenced by factors such as increased ventilation or absorption by materials. In contrast, the eco-friendly material unit experienced a rapid reduction in TVOC concentration, reaching levels below 1000 $\mu g/m^3$ after 14 days of construction. The concentration remained stable even after an extended period. Conversely, the general material unit took significantly longer, approximately 69 days, to reach TVOC concentrations below the threshold. This stark difference underscores the effectiveness of eco-friendly materials in mitigating TVOC emissions, aligning with previous studies [61,63,66] that have reported lower TVOC emissions in buildings utilizing eco-friendly materials.

On the other hand, the emission pattern of formaldehyde (HCHO) differed from that of TVOC. The highest peak of HCHO concentration was observed on the seventh day, reaching 126 $\mu g/m^3$ in the general material unit. Fluctuations in HCHO concentrations were attributed to variations in indoor temperature and humidity conditions. Despite maintaining a controlled indoor temperature of 23 ± 1 °C throughout the experiment, it is noteworthy that the air temperature measured in the central breathing area of the living room was approximately 2 °C lower than the set temperature of 25 °C. This temperature difference may have contributed to the observed fluctuations in HCHO emissions.

The analysis of major individual VOCs, excluding benzene, exhibited a similar declining trend in concentration over time, paralleling the pattern observed for TVOC. Notably, toluene demonstrated a substantial emission concentration, closely following the decreasing trend of TVOC. In contrast, benzene displayed distinct behavior with low initial emission levels and cyclic fluctuations over time. Except for benzene, the initial emission levels were significantly higher in general materials compared to eco-friendly materials. This underscores the effectiveness of eco-friendly materials in mitigating initial VOC emissions, thereby suggesting their superiority in indoor air quality.

From a practical perspective, these findings have significant implications for indoor construction and renovation practices. As supported by this study, eco-friendly materials can drastically reduce indoor air pollution, ensuring a healthier living environment for occupants. This insight is particularly important for urban settings where residents often face air quality issues, both outdoors and indoors. Additionally, the reduced emission levels from eco-friendly materials can lead to decreased health-related expenditures in the long run.

Our study also examined the effects of eco-friendly alternatives in specific material applications. Parquet flooring constructed with eco-friendly materials exhibited significantly lower TVOC emissions than conventional flooring materials. Although there was a slight increase in HCHO emissions over time, the difference compared to general flooring materials was not substantial (Figures 10 and 11). Similarly, eco-friendly wallpaper significantly reduced TVOC and HCHO emissions compared to general wallpaper, particularly on the first day after construction. By the sixth day, emissions levels equalized between the two types of wallpaper, with both showing significant reductions compared to the initial values. This demonstrates the long-term effectiveness of eco-friendly wallpaper in reducing emissions.

Regarding built-in furniture, utilizing eco-friendly materials significantly reduced TVOC concentrations compared to general materials. Although slightly higher HCHO emissions were observed on the first day in the bedroom, after seven days of construction, the emission levels were more than twice as low when eco-friendly materials were employed (Figures 14 and 15). Eco-friendly kitchen furniture, constructed with subsidiary eco-friendly materials, exhibited over two times lower TVOC emissions compared to general subsidiary materials. Applying UV paint as a surface finish was crucial in reducing VOC emissions. The overall emissions of HCHO were also lower in eco-friendly kitchen furniture.

Regarding door and window frames, both TVOC and HCHO emissions were slightly lower when eco-friendly auxiliary materials were employed. However, the difference in emissions was minimal, suggesting the need for further emphasis on applying eco-friendly materials in these components.

Furthermore, these results also guide the selection of materials for construction professionals, architects, and interior designers, promoting eco-friendly choices that offer environmental and health advantages.

The current study provides compelling evidence for the effectiveness of eco-friendly materials in reducing indoor air pollutants, particularly TVOC and HCHO. The temporal analysis of concentrations in various material applications underscores the significant benefits of eco-friendly alternatives. Nevertheless, further research and development are necessary to optimize the application of eco-friendly materials in specific components, such as wooden windows and doors. The findings from this study contribute to the expanding body of knowledge on indoor air quality, offering valuable insights for architects, builders, and homeowners striving to create healthier living environments. Future studies should focus on refining eco-friendly materials and investigating their long-term impact on indoor air quality and occupant health.

Moreover, with the global shift towards sustainability and the increasing awareness of health implications due to indoor pollutants, eco-friendly materials can also present economic opportunities for manufacturers and suppliers. Therefore, this study serves as an impetus for healthier living conditions and a call for industries to invest and innovate in eco-friendly construction materials.

It is essential to acknowledge that this study is preliminary. The findings provide compelling evidence for the effectiveness of eco-friendly materials in reducing indoor air pollutants, particularly TVOC and HCHO. The temporal analysis of concentrations in various material applications underscores the significant benefits of eco-friendly alternatives. However, it is important to note that this study did not consider relative humidity, which is one of the limitations. Nevertheless, further research and development are necessary to optimize the application of eco-friendly materials in specific components, such as wooden windows and doors. The findings from this study contribute to the expanding body of knowledge on indoor air quality, offering valuable insights for architects, builders, and homeowners striving to create healthier living environments. Future studies should focus on refining eco-friendly materials and investigating their long-term impact on indoor air quality and occupant health.

5. Conclusions

In this study, we compared the emission concentrations of formaldehyde (HCHO) and volatile organic compounds (VOCs) over time between eco-friendly and general materials in an experimental house. We also assessed emission characteristics in different areas of the house. The key findings are as follows:

TVOC emissions initially peaked and gradually decreased in houses constructed with eco-friendly materials, with the general material unit taking over 50 days to reach stable pollutant levels below 1000 $\mu g/m^3$. This suggests that using eco-friendly materials can create a more comfortable indoor environment over time. Overall, eco-friendly materials effectively improve indoor air quality.

In contrast, HCHO emissions reached their highest level on the seventh day and then stabilized. Other major VOCs showed declining concentrations over time, with benzene exhibiting cyclic patterns and toluene being the dominant influencer. General materials had higher initial emissions than eco-friendly ones, highlighting the efficacy of eco-friendly materials in reducing initial emissions.

Overall emissions were lower when using eco-friendly materials throughout the house. Eco-friendly flooring, wallpaper, built-in furniture, and kitchen furniture consistently demonstrated reduced emissions, particularly in the initial phase, showcasing the long-term effectiveness of eco-friendly materials.

Eco-friendly subsidiary materials contributed to lower TVOC and HCHO emissions, with kitchen furniture exhibiting significant reductions compared to general materials. However, window and door frame materials showed insignificant differences.

In summary, eco-friendly materials reduce indoor air pollutants, particularly TVOC and initial emissions. Toluene plays a significant role in VOC emissions, and eco-friendly materials outperform general materials in improving indoor air quality.

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