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# The Effect of Moderate Temperature Rise on Emitted Chemicals from Modern Building Materials

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**Abstract:** Chemical emissions from building materials may significantly impact indoor air quality and potentially human health, since individuals spend most of their time indoors. With rising global temperatures and more frequent heatwaves, building materials' resilience becomes more crucial for indoor air quality and structural integrity. However, the effects of temperature rise on building material emissions are not systematically studied. This study investigates the effect of a moderate temperature rise on the volatile organic compound (VOC) and aldehyde emissions of eighteen commonly used building materials, such as engineered hardwood, nylon carpet, terrazzo flooring, and acoustic tile, at two elevated yet realistic temperature points. The chemical emissions were collected using a micro-chamber setup and analyzed using thermal desorption/gas chromatography/mass spectrometry and high-performance liquid chromatography. The results showed that 78% of the materials tested demonstrated increased chemical emissions at higher temperatures. Wood-flooring materials showed statistically significant increases in formaldehyde at elevated temperatures, which could be associated with health risks. Eight of the tested materials, particularly those used in large surface area applications, showed significant increases in emissions at increased temperatures, and half of these were labeled as "low-VOC". These findings may inform the updating of building standards and third-party certification with respect to temperature variation when assessing building material emissions. This research aims to provide a comprehensive understanding of VOC and aldehyde emissions at emerging indoor environmental conditions due to extreme heat climate scenarios.

**Keywords:** indoor air quality; building materials; volatile organic compounds; climate change; resiliency; chemical emission



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## 1. Introduction

A changing climate affects both the outdoor ambient environment and the indoor air quality (IAQ) of the built environment. In the year 2023, the United States experienced 28 one-billion-dollar climate and weather-related disasters [1]. However, there could be more overlooked climate events globally. Meanwhile, increases in ambient temperature and an increased frequency of adverse weather events may result in changes in the chemical emission profiles in our immediate environments. The consequent effects indoors, such as increased temperature and humidity, may influence IAQ by releasing additional emissions of chemical contaminants like volatile organic compounds (VOCs) and aldehydes [2–4]. Noting the concentrations of these chemicals is important in establishing health-related outcomes, and Kanazawa et al. found that higher levels of semi-volatile organic compounds such as di-n-butyl phthalate were associated with greater reporting of sick-building-syndrome-related symptoms [3]. Markowicz and Larsson interrogated the effects of humidity on a limited list of materials and introduced the idea that humidity may be overlooked during routine monitoring of indoor air [4]. However, in these and other previous foundational studies that addressed the sources of chemical pollutants [5–7], the full capacity of the built environment to withstand emerging weather events such

as rising temperatures was likely neglected, and emissions were only evaluated under standard ambient conditions with a limited scope of building materials. The modern consumer has more choice than ever to specify the building products within their homes, offices, and schools, and a more tailored approach is necessary based on design, function, cost, and popularity within the scope of increasing adverse climate events. Therefore, the relationship between human health, chemical emissions, and the built environment should be revisited [2,8–10], and our study sought to address these important gaps in the research In this work, we explored a more comprehensive framework of building materials with respect to climate resiliency, specifically by evaluating the changes in emissions from materials used in our indoor environments under severe heat events.

Recent reviews on IAQ and the related chemical landscape due to changing climate conditions have noted a lack of study over the past five decades on the effects of weather events on building material emissions [9,10]. Only a narrow list of specific building materials has been studied for the link between indoor temperature, humidity, and the chemical emissions from building and other indoor products, examples of which include wood flooring, drywall, fiberboard, and vehicle carpet [11–15]. In all of these instances, the materials demonstrated increases in chemical emissions from increased temperature and humidity. Furthermore, one study noted that formaldehyde emissions from laminate flooring increased when temperature was evaluated at 29 °C and 50 °C [16], and another study concluded that the interaction of temperature and humidity led to increased emissions from medium-density fiberboard compared to temperature alone [12]. However, for the former study, 50 °C is not a realistic temperature, even in the increasing global temperatures we are experiencing. Additionally, while developing models such as diffusion coefficient calculations [17], Diel variation [18], and high-throughput modeling [19] to estimate the relationships between climate parameters and building materials is valued, it is important to comprehensively test more materials based on reliable and timely experimental setups [20–23]. And whereas standards for the chemical load of the indoor atmosphere have been created by many organizations dedicated to improving IAQ and human health [24–28], it may be necessary to understand the relationship of chemical emissions and the indoor environment in light of the changing patterns of ambient temperature that differ from normal testing and certification standards.

The current investigation hypothesized that there is an association between temperature rise and building material chemical emissions, with most products displaying moderate-to-severe increases depending on the product or situation. This has been shown previously [15,29–34]; however, this study goes in depth into common building material choices and real-world environmental conditions that may have been overlooked. In fact, several environmental monitoring studies have already recorded sustained indoor temperatures above 30 °C in different regions, especially among vulnerable populations with suboptimal HVAC systems or lack of air conditioning due to power outages [35–37]. Additionally, we hypothesized that against extreme temperature rises, such as would not be found under realistic conditions—temperatures of 50 °C, 60 °C, and even up to 80 °C [38,39], for example—moderate temperature rises corresponding to more realistic environmental scenarios would still lead to significant increases in VOC emissions.

To test this condition, we chose to utilize a more rapid, while still standardized, experimental procedure—the micro-scale exposure chamber—which could then, if desired by designers, builders, or homeowners, be modeled post hoc to investigate the human exposure impact. We used a validated micro-chamber setup to screen the emissions of eighteen building materials in a controlled environment. VOC and aldehyde emissions were collected by sorbent tubes and further analyzed via thermal desorption/gas chromatography/mass spectrometry (TD-GC/MS) and high-performance liquid chromatography (HPLC) with a comprehensive chemical library. Only the building materials themselves were studied; thus, the interference from other formulations, such as adhesives and finishes, was eliminated. This study can give insights into the implications of selecting materials that could be affected by a moderate rise in indoor temperature. In addition, the increased

emissions shown by this condition may inform the discussion of new or updated standards to improve our built environment.

## 2. Materials and Methods

### *2.1. Sample Selection and Preparation*

The modern building materials studied were chosen with the input of the American Society of Interior Designers (ASID) as part of a climate research initiative [40]. Materials were chosen based on their common market usage in large-scale development projects, modern new-construction homes, workplaces, and even school systems. A broad scope and choice of different material types was considered to provide a varied representation across the built environment. The cost considerations across these materials ranged from premium to basic brands. While flooring represented many of the materials chosen—to gauge the effect of higher surface area materials within a built space—several other types of materials were analyzed for their contribution to the chemical load (Tables 1–3).

**Table 1.** List of modern flooring samples studied. Price designations range from $ to $$$. The information in the table comes from Material Bank [41].

| Identifier | Material | Type | Composition | Designation | Price |
|---|---|---|---|---|---|
| Engineered hardwood flooring (EHF) | Wood | Flooring | Varnish, oak, wood/HDF, other wood | | $ |
| Laminate flooring (LF) | Wood | Flooring | Multi-ply + paper | | $ |
| Linoleum tile (LT) | Wood-containing | Flooring | 100% natural bio-based wood and resins | Natural/bio-based | $$ |
| Natural wood flooring (NWF) | Wood | Flooring | Solid 100% cypress | "Low-VOC" | $$$ |
| Vinyl composite tile (VCT) | Vinyl composite | Flooring | Vinyl composite | FloorScore certified | $ |
| Rubber flooring (RF) | Rubber | Flooring | Rubber | LEED low emitting | $$ |
| Terrazzo flooring (TF) | Terrazzo | Flooring | Epoxy resin, amines, fillers | VOC < 50 g/L | $$ |
| Porcelain tile (PF) | Porcelain | Flooring | Mineral earth | UL GREENGUARD Certified | $$ |
| Marble flooring (MF) | Marble | Flooring | Natural minerals | | $$$ |
| Olefin carpet (OC) | Olefin/PP | Flooring | Olefin/PP | | $ |
| Nylon carpet (NC) | Nylon | Flooring | Nylon | | $$ |

**Table 2.** List of modern ceiling samples studied. Prices range from $ to $$. The information in the table comes from Material Bank [41].

| Identifier | Material | Type | Composition | Designation | Price |
|---|---|---|---|---|---|
| Acoustic ceiling tile (ACT) | Synthetic/mineral | Acoustic tile | Resin plaster, marble sand, recycled minerals | "Low-VOC" | $$ |
| Felt acoustic tile (FAT) | Felt | Acoustic tile | Recycled PET, latex backing | | $$ |

**Table 2.** *Cont.*

| Identifier | Material | Type | Composition | Designation | Price |
|---|---|---|---|---|---|
| Drywall (DW) | Gypsum | Wall/ceiling | Gypsum, paper | UL GREENGUARD Gold Certified | $ |

**Table 3.** List of modern wall and textile samples studied. Prices range from $ to $$. The information in the table comes from Material Bank [41].

| Identifier | Material | Type | Composition | Designation | Price |
|---|---|---|---|---|---|
| Polyester metal wallcovering (PMW) | Polyester/metal | Wallcovering | PE/metallic foil | | $$ |
| Composite wall covering (CWC) | Composite | Wallcovering | Polymethyl methacrylate | UL GREENGUARD Gold | $$ |
| Vinyl textile (VTX) | Vinyl | Textile | Vinyl + urethane front/PE backing | Formaldehyde-free, "low-VOC" | $ |
| Polyester textile (PTX) | Polyester | Textile | PE + acrylic/proprietary backing | Indoor Advantage Gold certified (CA01350, LEED) | $$ |

Most materials were sourced from a web provider that designers and architectural professionals can utilize to gather insight data on products, share materials, and provide samples of the chosen materials [41]. Each building material was prepared by cutting two approximately fixed 16 $cm^2$ pieces (as sample duplicates) for testing. This study did not determine the age or storage conditions of the materials prior to receipt in the lab, as it intended to represent the real-world scenario when materials are sourced by consumers or builders. Products were studied independently and not as installations with additional materials. The prepared samples were stored from approximately one week to four months (in sealed Mylar® packaging) in between receipt and testing within the micro-chamber, and instrumental analysis was performed no more than five days after testing.

### *2.2. Material Testing Protocols*

A modified sampling procedure was based on the American Society for Testing and Materials (ASTM) method for micro-scale chamber testing (Figure 1) [42]. This method was chosen due to rapidity and reproducibility, as well as being previously validated. A Markes (Sacramento, CA, USA) µ-CTE micro-chamber/thermal extractor with four individual sampling wells was used with a pneumatics accessory to consistently control the airflow to each well. Each sampling well used for testing was conditioned at the appropriate temperature (26 °C and 35 °C) for one hour prior to placing the material inside. Each sample was equilibrated for 30 min, as suggested by the ASTM method [42], within the well before starting VOC and aldehyde sampling. A calibrated 0.2 L/min flow rate at nominal humidity (range 8–13%, with no suggestion given by the ASTM method) was continuously supplied to the chamber. VOC and aldehyde sampling took place at the outlet of the chamber with sampling times of 15 and 30 min, respectively, per technique. Chamber background samples were taken, one per each chamber, at both temperature setpoints before materials were placed inside the chamber. Testing was conducted using material duplicates and test sampling duplicates for a total of four measurements per building material. VOC samples were collected on Tenax® TA sorbent tubes (60/80 mesh, supplied prepacked by Millipore Sigma, (Burlington, MA, USA) according to Environmental Protection Agency (EPA) TO-17 [43], ASTM D6196 [44], and International Organization for Standardization (ISO) 16000-6 [45]. Aldehyde samples were collected on

2,4-dinitrophenylhydrazine (DNPH) cartridges (350 mg bed weight, supplied by Millipore Sigma) per ASTM D5197-16 [46] and EPA TO-11A [47].

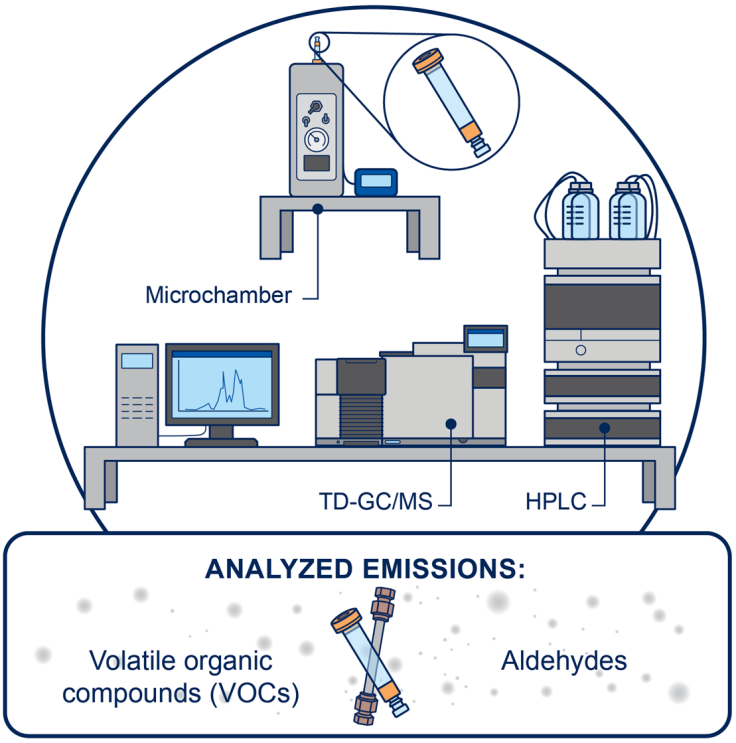


**Figure 1.** Methods diagram for the analysis of modern building materials.

### *2.3. Instrumental Analysis*

Volatile organic compound (VOC) analysis was performed using TD-GC/MS with an inline, automated Markes and Agilent (Santa Clara, CA, USA) combined system per the applicable methodologies [44,48]. The details of the thermal desorption, gas chromatography, and mass spectrometry instrumental parameters may be found in Supplementary Table S1. Generally, the TD method involved desorption of the sample tubes at 250 °C and direct transfer onto the GC via an inert transfer line. Mass spectral identification and quantitation of all separated compounds followed one of two routes. Several custom certified reference calibration standards (provided by Millipore Sigma) were analyzed to form six-point calibration curves (ranging from 35 ng/mL to 1000 ng/mL), which, when combined in the analytical software suite, totaled 136 known reference standards capable of comparison with each material sample and allowing direct quantitation if possible down to a sensitivity level of ng/mL (or parts per billion, ppb). The second route utilized the latest NIST mass spectral library [49] with a search criterium of greater than or equal to an 80% match score and the average instrument-calibrated toluene response factor for quantitation. The quality control measures for TD-GC/MS analysis are included in the supplemental information. The limit of detection (LOD) of analytical analysis is shown in Supplementary Table S2. If the individual VOCs that were directly quantitated were below the LODs present in the table, they were removed from the final results.

HPLC was used to analyze the DNPH cartridges for aldehydes following established, standardized protocols [46,47]. The specific method parameters may be found in Supplementary Table S3. Generally, the HPLC method used a gradient of water and acetonitrile to achieve separation followed by diode array detection at a specific wavelength for aldehydes. The detailed method description may be found in the supplemental information. Aldehydes found in each sample were identified based on retention time and ultraviolet (UV) spectrum matching to a calibration curve of 14 known aldehydes, and there were no unidentified peaks found that interfered with known compounds.

### 2.4. Data Analysis

Much of the data analysis in this study was performed with a combination of Microsoft Excel and GraphPad Prism (Version 10.2.3). Total volatile organic compound (TVOC) calculations were performed by summing the air concentrations in toluene equivalents for all compounds from n-$C_6$ to n-$C_{16}$ according to the standard ISO definition [45]. Emission factors (EF, $\mu g/m^2 \cdot hr$) were calculated via Equation (1) below [50]:

$$EF = C \times \frac{N}{L} \quad (1)$$

where $C$ is the VOC concentration in $\mu g/m^3$; $N$ is the air change rate in air changes per hour; and $L$ is the loading factor, which was the size of the material (16 $cm^2$) divided by chamber volume (0.000114 $m^3$).

Statistical analyses were performed in GraphPad Prism, and paired *t*-tests were run for each chemical within each data set with no corrections for multiple comparisons and a *p*-value of less than 0.05 for significance.

### 2.5. Indoor Exposure Modeling

An indoor exposure model was applied with observed VOC emission rates to estimate potential inhalation exposure concentrations in a single-family house, representing typical daily exposure indoors at home. The model was based on a steady-state mass balance, assuming the building materials are the only sources in well-mixed rooms [25,50]. The revised model is shown in Equation (2):

$$C_i' = \frac{\sum_j (EF_{ij} \times A_j)}{V_m \times ACH} \quad (2)$$

where $C_i'$ ($\mu g/m^3$) is the estimated concentration of compound $i$; $EF_{ij}$ is the emission factor of compound $i$ from material $j$ based on micro-chamber characterization; $A_j$ ($m^2$) is the area of the material $j$; $V_m$ ($m^3$) is the volume of the model room; and $ACH$ ($h^{-1}$) is the air change rate of the model room. The residential model scenario was adopted from previously published standard methods [50,51], which was a single-family house with four bedrooms and two bathrooms, taking a floor space area of 211 $m^2$ and a simple total volume of 547 $m^3$. From the referenced model, this was determined to be an average-size house in the United States and well representative of the conditions across the tested materials. In this study, we modeled the exposure concentrations in the living room and the master bedroom; the conditions of these two rooms are shown in Table 4. In addition, the air change rate ($ACH$) was 0.23 $h^{-1}$ in the house representing a modern home with energy-efficient features and a more sealed building envelope.

**Table 4.** Conditions of the model rooms.

| | Floor/Ceiling Area ($m^2$) | Wall Area ($m^2$) | Volume ($m^3$) |
|---|---|---|---|
| Living room | 59.46 | 42.74 | 163.1 |
| Master bedroom | 16.96 | 19.76 | 38.92 |

## 3. Results and Discussion

### 3.1. Total Volatile Organic Compound Emission

TVOC generally represents the overall chemical emissions from the tested samples. In our study, the TVOC concentrations and corresponding emission rates of the materials at 35 °C exceeded those at the room temperature measurements, apart from natural wood flooring, drywall, composite wall covering, and polyester textile (Figure 2). The products showing greater emissions at 35 °C included engineered hardwood, nylon carpet, mineral

acoustic ceiling tile, and terrazzo flooring, with emission rates ranging from 2 to 5 times higher than those at 26 °C.

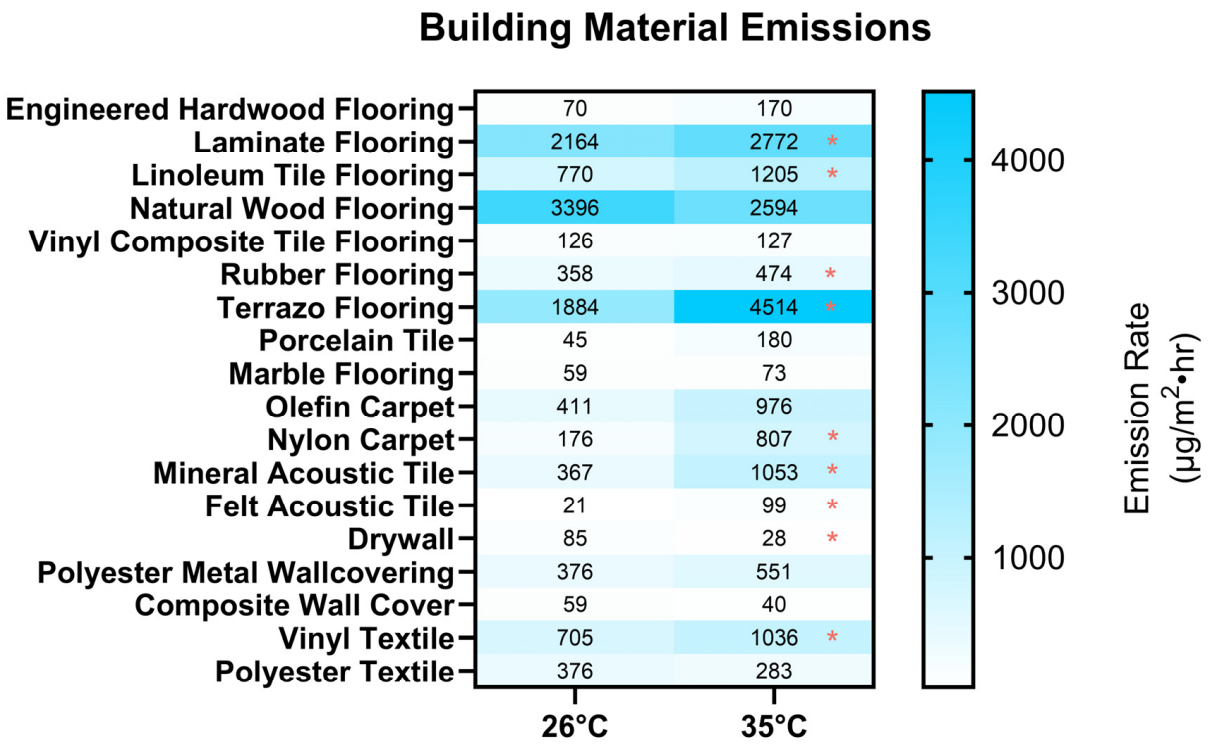


**Figure 2.** Average TVOC emission rates of 18 modern building materials at two studied temperatures. The * denotes significant change ($p < 0.05$) in emission rate between the two temperatures. Within each material grouping type, the heatmap is organized by increasing price.

Eight of the eighteen materials showed statistically greater emission rates than at room temperature. Some of the higher emitting materials like laminate flooring, linoleum tile, and natural wood flooring are wood-based products, known to emit higher levels of biogenic and extractive VOCs depending on the source and manufacturing process [52].

It should be noted that, given the increase in TVOC emission rates under moderate temperature increase, the building materials or indoor environments that have complied with regulations at typical room temperature may exceed the reference levels at a 10 °C elevation in temperature. The product verification programs that are used routinely to inform specifiers of healthy and sustainable spaces do not typically encompass elevated temperatures for any path of certification or verification. Additionally, it is highly relevant that per the United States Green Building Council's LEED standards, the first option for certification credit, which does not include VOC testing or meeting indoor air quality metrics, includes a "building flush-out conducted at a temperature no greater than 80 °F (27 °C) and relative humidity no greater than 60%" [28]. This option could potentially not remove contaminants within the building once it is occupied, given our results, in the rising global temperatures predicted should the screening of the building proceed by this method. And while this study only reports chemical emissions from small, representative samples of the materials in which the surface and four sides were exposed—without accounting for adhesives or installation methods—it provides noteworthy evidence that at a much larger scale, modern building materials may still negatively impact indoor air quality.

### *3.2. Individual VOCs*

The first important trend to note at the level of individual VOCs from our investigation was the number of VOCs detected that were unique to the elevated temperature conditions (Figure 3). For the two carpets, the mineral acoustic ceiling tile, and the porcelain tile

samples, the number of distinctive VOCs produced at 35 °C accounted for at least half of the total count of VOCs. For the remaining materials, they accounted for 18%–44% of the total VOC counts, except for drywall. This result suggests that even with a moderate temperature rise in the built environment, it may introduce new chemicals that are not monitored with current testing and certification protocols. It should be noted that VOC emission indoors is not a static process but can change and produce additional VOCs and new sources of VOCs influenced by natural and anthropogenic transformations and patterns [53,54].

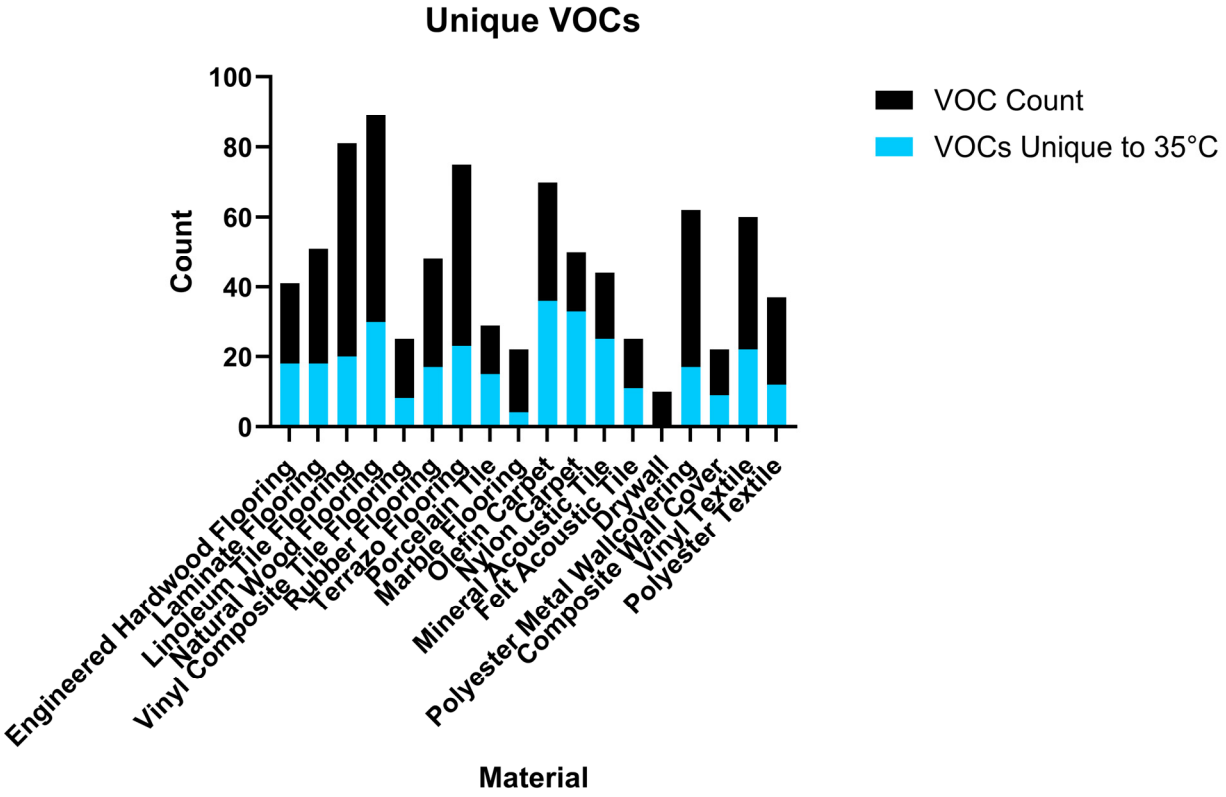


**Figure 3.** Average number of individual VOCs detected from each studied building material.

The detection frequency was calculated using the number of times the chemical was detected divided by the total number of samples (Figure 4). Specifically, acetone was found in all samples, and the rest of the commonly detected chemicals included aldehydes, alcohols, and organic acids. Eleven of the top fifteen frequently detected chemicals are listed in various governmental and non-governmental agency risk tables, such as the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs), eco-INSTITUT Germany GmbH (AgBB) Lowest Concentration of Interest (LCIs), National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limits (RELs), and the Occupational Health and Safety Administration (OSHA) Permissible Exposure Limits (PELs).

Phenol, present in ten of eighteen materials but listed as International Agency for Research on Cancer (IARC) Group 3 and not classifiable in terms of carcinogenicity, may cause irritation to the eyes and respiratory system [55]. Additionally, almost all the top fifteen compounds found in these modern building materials are commonly known to negatively impact IAQ and are associated with proven, potential, or uncertain health effects. Therefore, these baseline and temperature-related increased emissions warrant additional scrutiny [56]. Notable results from the product groupings chosen in our study are discussed in more detail in the following sections.

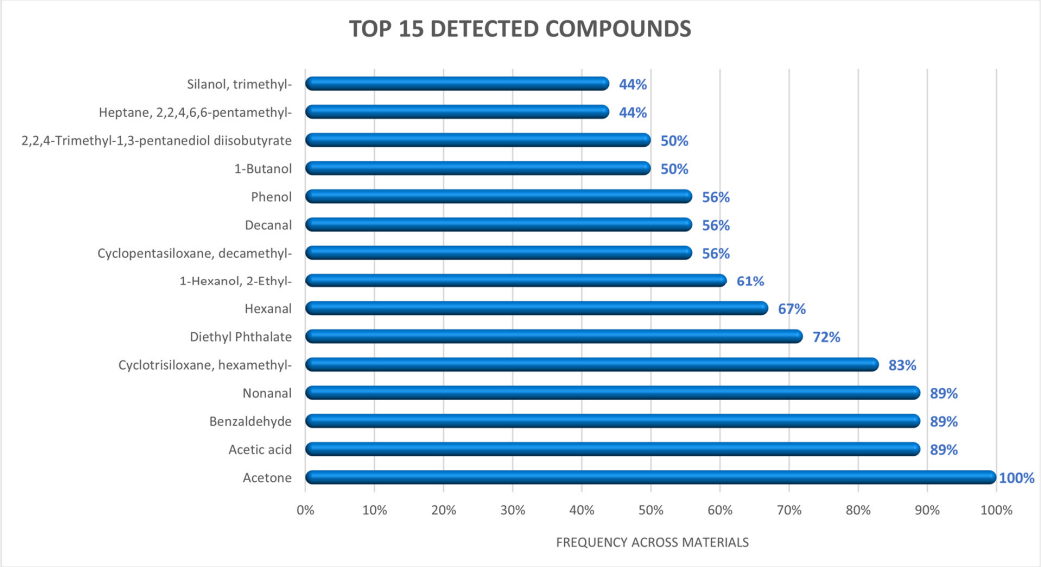


**Figure 4.** Top 15 of the most frequently detected chemicals across all 18 building materials.

### *3.3. Wood-Based Flooring*

Many individual VOCs were present in the wood-flooring samples that were statistically significantly higher at moderately elevated temperatures (Figure 5), although many were identified as deriving naturally from the woods themselves [52,57]. Examples included nonanoic acid, furfural, and several terpene and sesquiterpene compounds. The chemicals of health concern that had increased emissions at higher temperatures included diethyl phthalate, acetic acid, and various medium-chain aldehydes like pentanal and hexanal. These were found within linoleum tile and natural wood flooring, which had the greatest number of VOCs.

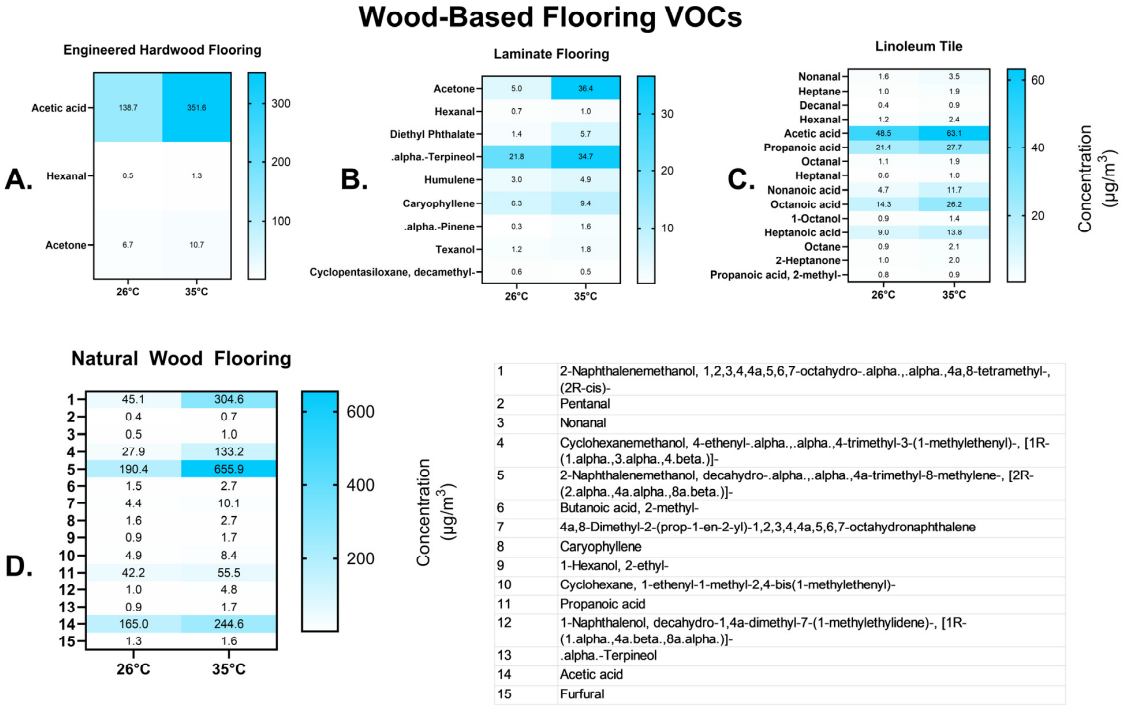


**Figure 5.** Average concentrations of VOCs with significantly different ($p < 0.05$) emissions at elevated temperatures from each wood-based flooring material. (**A**) EHF material; (**B**) LF material; (**C**) LT material; (**D**) NWF material. Chemical names in D are labeled to the right of the panel.

Although most VOC concentrations are below the LCI levels suggested for chamber evaluations for building materials, it is important to note that health regulations are not always based on the most sensitive health endpoint or necessarily indicative of impacts on sensitive subpopulations. However, the levels detected in the current study were lower established thresholds for health toxic effects [58,59], and this may have been due to the unknown age of the samples, where a steady state could have been taken into consideration. Finally, one significant finding from this product class was formaldehyde, which was detected only in the wood-based samples (Figure 6). Formaldehyde is an IARC Group 1 respiratory carcinogen [55], and more than three decades of research have confirmed its adverse health effects, which are still being elucidated [60]. The formaldehyde levels from engineered wood at 35 °C (159.2 µg/m$^3$) exceeded the EPA/ATSDR reference concentration (RfC) in the latest toxicological review on inhalation of formaldehyde [61]. In addition, the consumer and household reference levels are more restrictive, since they were established based on toxicological research aimed at vulnerable populations, such as infants, children, and others.

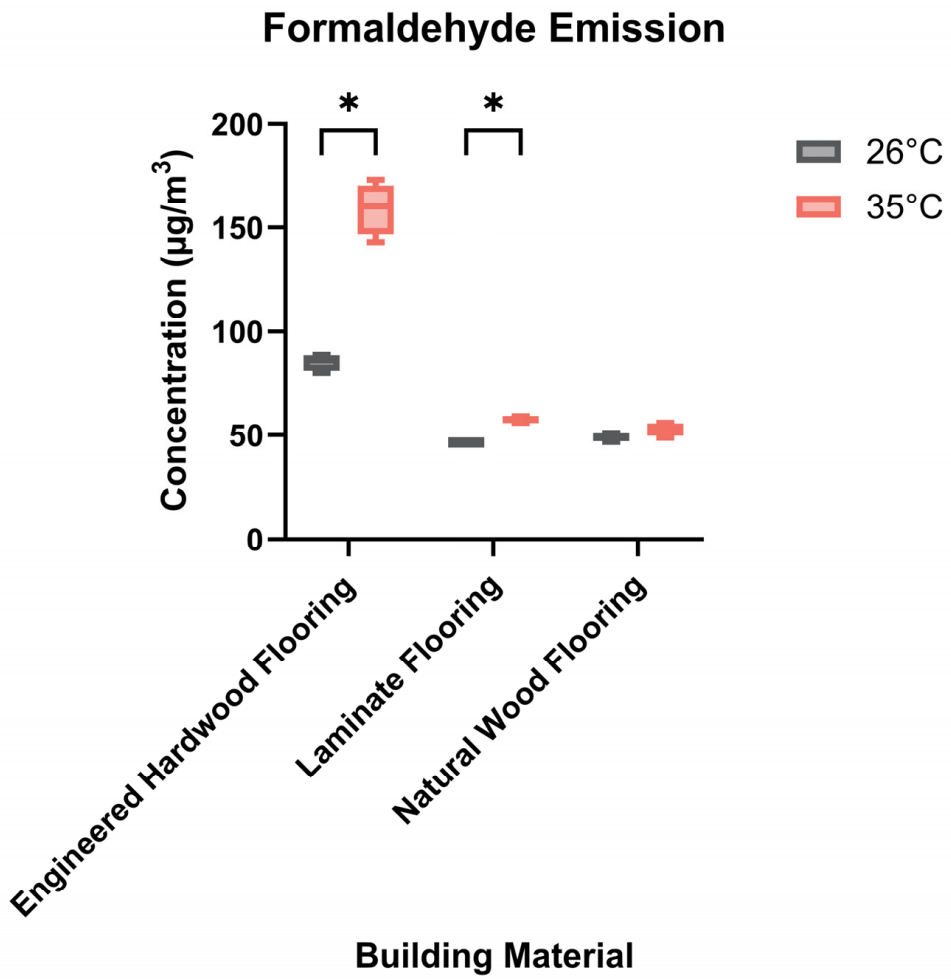


**Figure 6.** Average formaldehyde levels from wood-based flooring at different temperature conditions, with an asterisk indicating significance ($p < 0.05$).

### *3.4. Carpet Flooring*

The olefin and nylon carpet samples tested in this study (Figure 7) had relatively lower VOC levels compared to the harder surface materials. However, some of the studied carpets seemed not to adhere to the Carpet and Rug Institutes (CRI) Green Label certification program, which includes VOC emission target air concentrations and maximum emission factors [62]. For example, the emission rate of nonanal in the less expensive olefin carpet

in our study, approximately 190 μg/m$^2$·hr, exceeded the CRI emission factor criterium of 24 μg/m$^2$·h for a 14-day test. It should be noted that we did not account for longer testing periods. Additionally, the caprolactam in our sample of nylon carpet exceeded the emission factor criteria of 131 μg/m$^2$·h within a 24 h scope by more than two times at 307 μg/m$^2$·h. From a human health exposure perspective, caprolactam is an upper respiratory irritant like many of the chemicals found in these building materials [63]. Infants and children, who spend more time on the floor than adults and adolescents, have the potential for greater exposure from these materials because carpets are more friable and prone to wear than other flooring choices. And dibutyl phthalate, discovered in olefin carpet, is a known endocrine and reproductive toxicant, causing gut microbiome stress and testicular spermatogenesis effects, respectively [64,65].

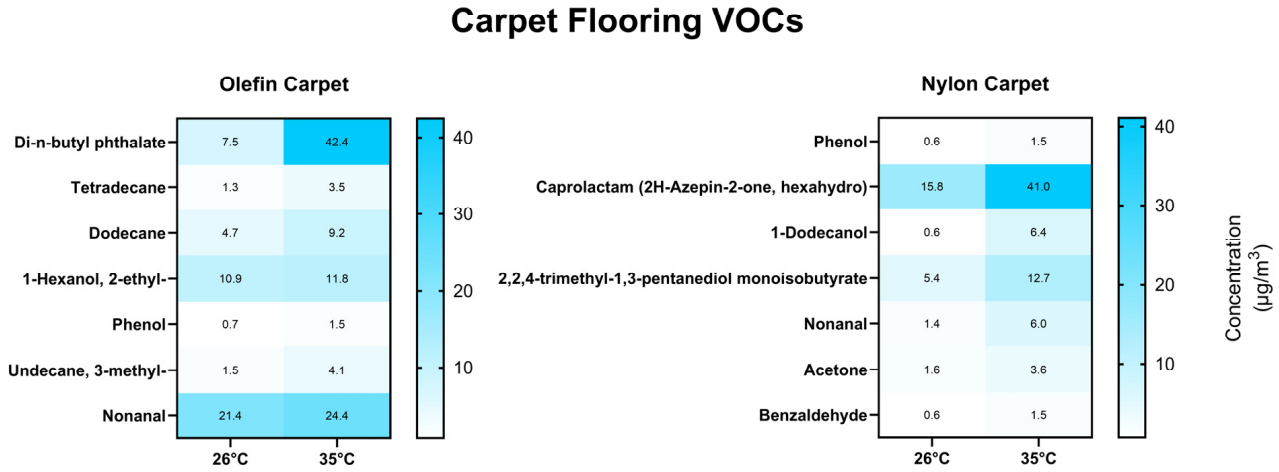


**Figure 7.** Average concentrations of individual VOCs showing significant ($p < 0.05$) changes in emissions from carpeting at two temperatures.

### *3.5. Other Flooring Materials*

Vinyl composite tile, a material commonly used in schools, workplaces, and gymnasiums, only had one significantly different compound that displayed increased concentration at 35 °C, which was 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate. This compound was also present in the studied nylon carpet and in 31% of the samples. A few individual VOCs were identified that are relevant to human health outcomes from rubber flooring and terrazzo flooring (Figure 8). Rubber flooring contained butylated hydroxytoluene (BHT), which has known health effects in animal models [66], as well as the potential to influence BMI and asthma outcomes in children [67]. The presence of BHT also confirmed the recycled nature of the rubber flooring specified by this particular manufacturer's technical data sheet, since BHT has commonly been found in reprocessed tires that make up playground rubber mulch [68] and soccer fields worldwide [69]. Our study also confirmed that BHT was able to volatilize and impact IAQ at a moderate indoor temperature rise. Marble and porcelain flooring did not exhibit any appreciable VOCs or significant changes in emission rates from room to elevated temperatures, most likely since these are made of natural minerals and are hard, dense materials not expected to emit concerning chemicals. Additionally, the porcelain tile was certified to be low-emitting. Terrazzo flooring represented the highest TVOC emitting material in the study, and this was mainly due to the high emission of hexylene glycol, a known solvent plasticizer and binder used in construction. Two benzene analog compounds in the terrazzo flooring emissions—propylbenzene and 1,2,4-trimethylbenzene—have been noted to produce high ecotoxic effects in aquatic animals [70], and 2-ethylhexanol has a long legacy as an indoor air contaminant with a record for human health effects and sensitivities [71].

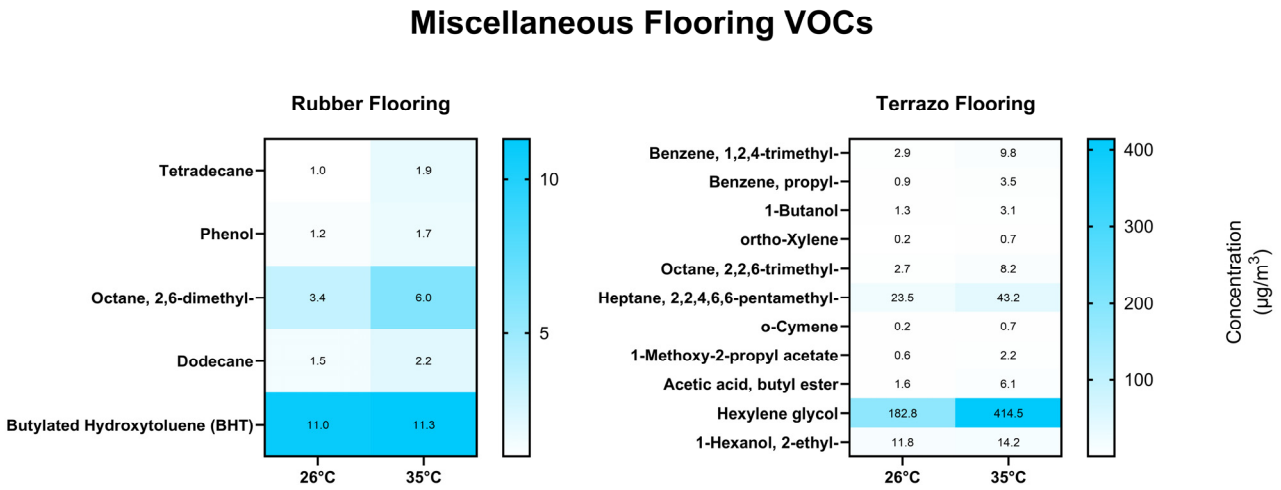


**Figure 8.** Average concentrations of individual VOCs showing significant increases ($p < 0.05$) from other flooring materials at two temperatures.

### *3.6. Miscellaneous Building Materials*

Three other groups of building materials—acoustic tiling, wallcoverings, and textiles—were represented in the remainder of the samples tested. Drywall, composite wall covering, and polyester textile samples had chemical emission factors that decreased with a moderate increase in temperature. The reason behind this phenomenon was unclear. One factor that could be associated was the adsorption/absorption capacity of the building materials. One relatively prevalent chemical present in these miscellaneous materials was benzothiazole, found in 31% of all materials tested in the study and 50% of the wall and textile-related samples. Benzothiazole is an irritant found in a variety of industries and product environments [72]. In our study, benzothiazole was the second highest emitter, significantly higher at 35 °C, for both polyester wall covering and textile. Phenol was approximately 1.5 times higher within moderate temperature rise in the polyester metal wallcovering sample. Among the two textile materials—vinyl and polyester—the common compound that had increased concentration at elevated temperature was *p-tert*-butylphenol, a chemical used in stabilizers, coatings, and adhesives. This chemical has joined the many others that are now being found to cause intestinal stress and microbiome effects [73], of which the latter has become a burgeoning realm of research related to human health. Finally, while the mineral-based acoustic ceiling tile was designated "low-VOC" by the manufacturer, this did not necessarily match up with the results seen here. It was the highest emitting miscellaneous material (Figure 2), and "low-VOC" may have only referred to certain target list VOCs. This is an important distinction to make, as there may be manufacturer-specific lists of VOCs that are not revealed to the public when making these product statements. The consumer or user is unaware of these potentially arbitrary criteria. While these miscellaneous building materials are often neglected when thinking about the built environment space, they represent a large portion of indoor surface area comparable to flooring.

### *3.7. Modeling of Exposure Levels in a Single-Family House*

TVOC exposure levels were estimated using the selected materials (Table 5). For the modeled living room, engineered hardwood flooring was selected to represent a low-emitting flooring material, and terrazzo flooring was selected to represent a high-emitting material. For the modeled master bedroom, carpet was used as the flooring material. Drywall without covering was input as the wall material for both rooms. TVOC estimation was conducted for both normal room temperature and a moderate temperature rise (Table 5). Only two scenarios in the modeled living room (felt acoustic tile and engineered hardwood flooring) showed exposure concentrations lower than the LEED TVOC level (500 µg/m$^3$) [28]. There were 62.5% and 87.5% of the material combination scenarios

with estimated TVOC concentration exceeding 1000 $\mu g/m^3$ at normal room temperature and elevated temperature separately. With a moderate temperature rise, room TVOC concentration increased 1.9–3.2 times. The highest estimated TVOC concentration reached over 8000 $\mu g/m^3$, which involved the two high-emitting materials (terrazzo flooring and mineral acoustic tile). It should be noted that this model investigation tended to estimate worst-case scenarios for the selected materials. Only emissions from the materials were considered, and no potential sinks in the room were included in the model, which may overestimate the exposure levels. In addition, increasing the air change rate could reduce exposure levels; for example, an air change rate of 0.5 $h^{-1}$ could bring the highest estimated concentration down to approximately 4000 $\mu g/m^3$ and over 30% of the concentrations within 500 $\mu g/m^3$.

**Table 5.** Model estimated exposure TVOC concentrations ($\mu g/m^3$) in the living room and master bedroom with different flooring and ceiling materials.

| | | **Mineral Acoustic Tile** | | **Felt Acoustic Tile** | |
|---|---|---|---|---|---|
| | Temperature (°C) | 26 | 35 | 26 | 35 |
| Living Room | Engineered Hardwood Flooring | 789 | 1970 | 241 | 458 |
| | Terrazzo Flooring | 3664 | 8855 | 3116 | 7343 |
| Master Bedroom | Olefin Carpet | 1662 | 3906 | 1007 | 2098 |
| | Nylon Carpet | 1217 | 3586 | 562 | 1778 |

### *3.8. Limitations*

There were several limitations in this study that need to be acknowledged. First, we did not attempt to trace the origin or storage of these materials before testing. This was not necessary for the scope of this study because we wanted the materials to be age- and storage-agnostic to study the effects in a real-world scenario. Materials purchased by a designer or consumer are not investigated for their age and storage but based on our results still emit significant levels of pollutants. Additionally, this was not standardized testing for architectural approval but rather intended to investigate emissions at differing temperatures that indoor climates are already beginning to experience. Humidity was not considered, as it was beyond the scope of this initial study; it could be included in future work. We did not seek to correlate our results with those of small or large chamber testing protocols, where humidity and longer exposure times could be addressed. Also, per ASTM D7706 (the micro-chamber testing method), the results can be compared to standard emission tests like larger chamber tests by way of establishing a reference control value [42]. However, the samples used to perform these tests must be immediately taken from the same batch of samples, typically within hours of manufacture directly from the factory. The reference tests are typically time-consuming and disadvantageous toward the type of screening routinely performed by industry and analogous to that undertaken in our study. Degradation and contamination of the materials before receipt was not expected but possible due to differing warehouse conditions or potential environmental exposures. Once received, however, this possibility was minimized. Another limitation is that the emission characterization did not account for the decay of emissions over extended time—for example, the 28-day window or the 24 h test. However, the objective of this study was to solely investigate the temperature effect by routine screening. Additionally, the decrease in emission factors for natural wood flooring, drywall, composite wall covering, and polyester textile was an unexpected result and could not be explained by our testing procedures. Based on this fact, further future empirical testing is necessary, which could include alternate testing methods, such as small chamber testing and more sizable portions of materials with differing conditions. Finally, this study estimated the potential exposures using a modeling approach for a typical residential home setting. Other scenarios, such

as the ventilation rate, room furnishings, and aging of materials, may also affect exposure. This may be investigated in further studies.

## 4. Conclusions

In an increasingly changing climate worldwide, our indoor environment deserves extra scrutiny in relation to the materials that make up the built space in which we live and work. While limited work has been conducted in the past regarding building materials and the effects of temperature and humidity, our work highlighted a more comprehensive approach utilizing deliberate design choices and real-world temperature conditions that may be expected soon. Overall, the VOC emissions of a variety of modern building products increased with a moderate rise in indoor temperature, representing a lack of air conditioning or sub-optimally conditioned indoor space. Of the studied materials, 78% showed increased TVOC emissions at elevated temperatures, with nylon carpet and the two acoustic tiling materials having the greatest increase (at least three to five times greater). Specifically, the flooring and ceiling materials were more likely to increase emissions under elevated temperatures, while the wall and textile coverings tended to be less affected by the change in temperature. Some hazardous VOCs, such as formaldehyde, caprolactam, and dibutyl phthalate, were found to produce emissions at higher levels with the increase in temperature. The results were not associated with material cost, meaning that cheaper materials did not necessarily result in more VOC emissions in either temperature condition or vice versa. Model estimations with the selected materials, which showed the exposure levels of TVOCs in a single-family home, likely exceeded the suggested LEED levels. This is especially concerning given the vulnerable populations meant to be protected by product designations and certifications and certainly raises the question of adequacy in testing in an environment that has not been characterized accurately in its chemical load. Since the general population spends most of its time indoors, building materials still represent the largest surface area of potential indoor air contaminant sources encountered, and much more investigation and increased awareness of this issue are necessary to safeguard our health. There is a need for future research focused on the interaction of additional environmental variables like humidity, ventilation rate, and material aging that are impacted by climate change. How the changing climate may impact indoor air quality based on the types of construction materials and furnishings is also required to address the potential impacts they may have on overall indoor environmental quality.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14113683/s1. Table S1: Thermal desorption/gas chromatography/mass spectrometry (TD-GC/MS) parameters; Table S2: TD-GC/MS limits of detection (LOD) for 57 compounds; Table S3: High-performance liquid chromatography (HPLC) parameters.

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