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Review

Impact of Carpets on Indoor Air Quality

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Abstract: Interest in having a healthy and well-being environment has increased the awareness to improve indoor air quality (IAQ). Building materials influence the contribution of indoor air pollution, so understanding their behaviour on IAQ is essential. Among building materials, carpets cover surfaces of indoor environments and significantly impact IAQ due to their large surface area and multi-layers of materials components. This review aimed to consolidate what is known about how carpet impacts indoor volatile organic compounds (VOCs) concentrations and particulate matter (PM) distributions. The results showed that carpets are not only a source of primary emission but also can ad/absorb VOCs and emit VOCs through secondary emission, sink effects, and transformation reactions. The material composition of each carpet layer, environmental parameters (e.g., humidity, temperature, air velocity), and chamber size influence a carpets' behaviour. Previous studies on the resuspension of PM from carpets mainly focused on the effects of human activities and humidity. Further studies are needed to enhance knowledge related to carpet behaviours in the indoor environment and on how the common materials of carpets should be designed and sustained to reduce exposure to harmful pollutants indoors while maintaining its benefits.

Keywords: carpets; indoor air quality; emission; sorption; VOCs; particulate matter

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1. Introduction

Nowadays, people in the Western world spend most of their time (80–90%) indoors, where indoor air quality (IAQ) affects occupants' health and well-being [1]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined IAQ as "the types and concentrations of contaminants in indoor air that are known or suspected to affect people's comfort, well-being, health, learning outcomes, and work performance" [2].

Two main classes of these contaminants consist of gaseous compounds (e.g., organic and inorganic gases) and particulate matters (both biological, including allergens, potential pathogens, and non-biological) [2]. Most of these compounds have a concentration consistently higher indoors than outdoors, affected by minimalization of ventilation (including infiltration) as a result of energy-saving measures [3]. Organic gases, comprising volatile organic compounds (VOCs, organic compounds with boiling points between 50 and 260 °C), very VOCs (VVOCs), and semi-VOCs (relatively low volatility VOCs), may cause several health problems, such as nose, eye, and throat irritation, loss of coordination, headaches, nausea, damage to the kidney, liver, and central nervous system, etc. [4]. Even though, most of the common VOCs in the buildings' indoor environment are considered nonreactive (NRVOCs), exposure to low concentrations of NRVOCs mixtures may cause human sensory irritation. Additionally, some VVOCs like formaldehyde show various health effects on humans, from irritation to sinonasal and nasopharyngeal cancer, even in low quantities [5]. Inorganic gases such as nitrogen oxides (NO_2), carbon monoxide (CO), and carbon dioxide (CO_2) are mainly produced by combustion, such as gas cooking and fossil fuel burning. The concentration of inorganic gases indoors depends on the unvented gas heaters and cookers, ventilation system, season, and outdoor levels [6]. Nowadays, the concentration is limited due to the application of electrical heating systems and application of mechanical ventilation.

Another pollutant studied by many researchers is particulate matter (PM). PM refers to a broad class of chemical and physical substances that exist as liquid droplets or solid particles of various sizes [7] and is an important indicator of air pollution. Depending on their size, PM includes inhalable coarse particles (PM_{10}) and fine particles ($PM_{2.5}$) with particulate sizes below 10 μm and 2.5 μm, respectively. There is also a category of ultra-fine particles ($PM_{0.1}$) with less than 0.1 μm diameter, which a few researchers considered for studying carpets' behaviour. PM affects human health through respiratory symptoms, cardiovascular diseases, and lung cancer [8]. Generally, past epidemiological and toxicological research showed that smaller PMs have higher toxicity through mechanisms of oxidative stress and inflammation [9].

Remarkably, two major sources of organic compounds and PM can be found indoors, namely: people and their activities (such as heating, cooling, cooking, using printers, photocopiers, etc.), and emissions from building materials [10]. The latter source of pollution is particularly interesting for its emission of organic compounds, while the first of both PM and VOCs. Building materials comprise finishing materials, such as paints and varnishes, treated and processed wood-based composite materials for furniture and finishes, and elements made of plastics and fibre textiles. The VOC concentrations emitted from building materials depend on the substance and the preparation of the building materials, the time elapsed from installation/use (for example, in the case of carpet, VOC emissions are in general the highest when applied and decrease over time) [11–13]. PM concentrations depend on the activities performed indoors, the exchange with outdoor air, and the (re)suspension of particles from indoor surfaces, such as flooring materials.

Previous studies found that building materials with high surface area (floors, walls, and ceilings) reflect an important role in IAQ through emission and sorption of contaminants to and from the air. Flooring materials typically cover large areas and consist of multi-layers of different materials [3], significantly impacting IAQ. Flooring materials can be divided into basically two categories: smooth or hard flooring materials (e.g., wood, linoleum) and soft or fleecy materials (e.g., carpet). Among the flooring materials, carpets can significantly impact IAQ because of their large surface area in buildings, when applied, in combination with the large surface area of the dense fibre piles. The carpet piles consist of about 10 million fibres per square meter that provide various functional compounds for emission and sink effects on air pollution [14]. Therefore, numerous researchers have studied the behaviour of carpets on IAQ, of which some considered the perception of IAQ by sensory evaluation of people using their noses, called perceived IAQ [15,16], and others used chemical measurement techniques [17]. Human exposure to VOCs can be through inhalation, dermal contact, or ingestion [18]. Both inhalation of the indoor air and suspended particles, and dermal contact with a flooring material that emits VOCs or adsorbs the VOCs from other components, have shown a whole range of effects, from low to severe health effects [19,20]. The settled dust on the floor may be ingested through resuspended dust from the floor surface. Moreover, the suspension of dust can affect the concentration of VOCs in an indoor environment [21], especially regarding semi-VOCs [22].

In the light of the current need for improving IAQ, it is questioned how carpets contribute to that IAQ both from the polluting (e.g., emission and resuspension) and the cleaning effect (e.g., ad/absorption) point of view. This literature review was performed to answer the following questions. What do we know about the effects of carpets on IAQ? In addition, do different carpet material components and different environmental conditions affect the behaviour of different carpets on IAQ?

2. Methodology

Several keywords were used to identify relevant scientific publications, such as "carpet," "VOC," "particulate matter," and "dust" (Figure 1). Hence, the papers were searched according to their title, abstract, and keywords utilising the SciFinder, Scopus, and Google Scholar search engines. Studies that mainly investigated carpets on IAQ were included in the shortlisting process. More than 273 papers were collected in this way. They were then shortlisted based on the applicability of their titles and critical information provided in their abstracts (more than 99). After that, the results were reviewed to check and filter the output associated with materials components of carpets to have a comprehensive understanding of the behaviour of carpets regarding IAQ. Then, the behaviour of carpets regarding VOCs was categorized as emission, sink, and transformation effects (Section 3.1), and the behaviour of carpets regarding PM was categorized as deposition and resuspension of particles (Section 3.2). Inorganic gases were not considered in this review because only few researchers studied the behaviour of carpets regarding inorganic gases and because the concentrations of these gases indoors are limited.

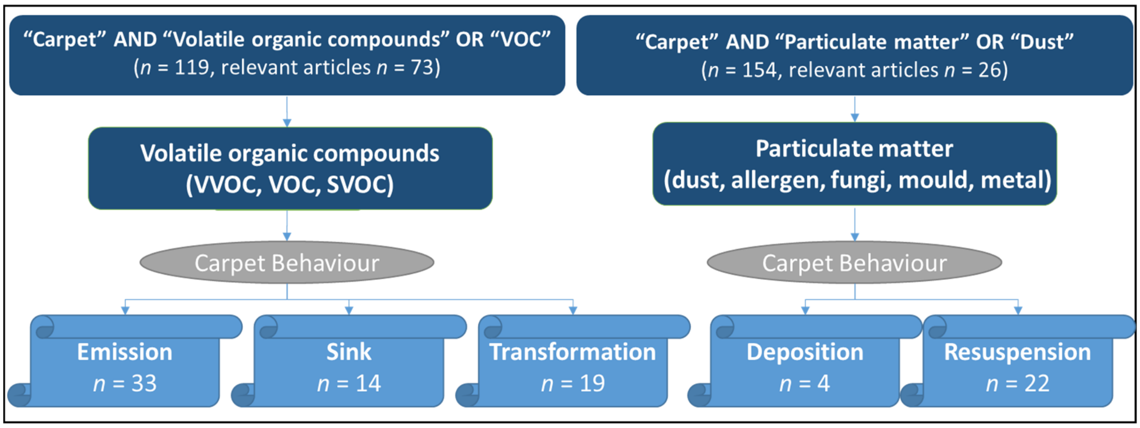

Figure 1. Keywords used for collecting literature and the number of relevant articles.

To the authors' best knowledge, all the available reviews on the impact of carpets on IAQ were published without considering the carpet materials types. Considering the fact that change in using different material compositions in carpets does affect the behaviour of carpets in terms of IAQ, it is essential to study this aspect.

The findings of the review are discussed, along with the effects of carpets on IAQ with regards to (1) VOCs in Section 3.1; and (2) particulate matter in Section 3.2.

3. Effects of Carpets on IAQ

A typical carpet is a three-dimensional porous textile with use-surface (pile yarns) and backing. The backing of the most dominant carpet, a tufted textile floor covering, consists of primary backing, secondary backing, and adhesive glue (Figure 2). Pile yarns are inserted into a previously manufactured primary backing (e.g., polypropylene (PP) or polyester (PET)) by needles like sewing machine needles, and then secured [23]. The secondary backing component (e.g., PP, PET, polyvinyl chloride (PVC), jute, or bitumen) joints the back of the upper layer (use-surface and primary backing) with adhesive glue (e.g., styrene butadiene-rubber (SBR), ethylene vinyl acetate (EVA), polyethylene, or polyester) [24].

The pile yarn, made of dense fibres with high surface area, affects most carpet properties, such as resiliency, heat insulation, and acoustical behaviour [25,26]. In general, carpets are divided into natural and synthetic types and mixtures based on pile materials (Figure 2). Natural carpets are fabricated from animal or plant sources like wool, hair, silk, coir, sisal, cotton, or mixtures. Synthetic carpets are fabricated with synthetic polymeric materials like polyamide (PA), PP, PET, polyacrylonitrile (PAN), or mixtures of these materials, or a mixture of synthetic fibres and natural fibres [24,27].

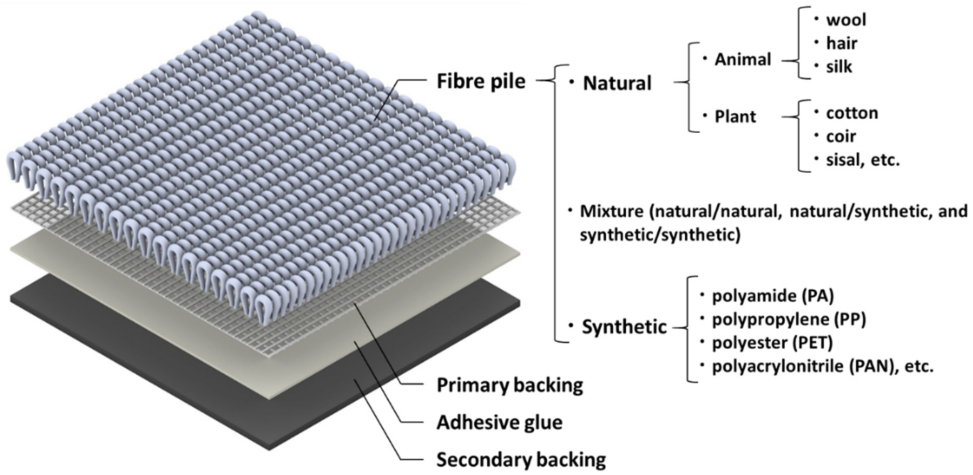

Figure 2. The structure of carpets and categorization of the natural and synthetic fibre carpets.

3.1. VOCs

In general, carpets can impact the concentration of VOCs in the indoor environment through emission, sink effect (sorption and re-emission), and transformation (Figure 3). These processes are discussed in the following sections.

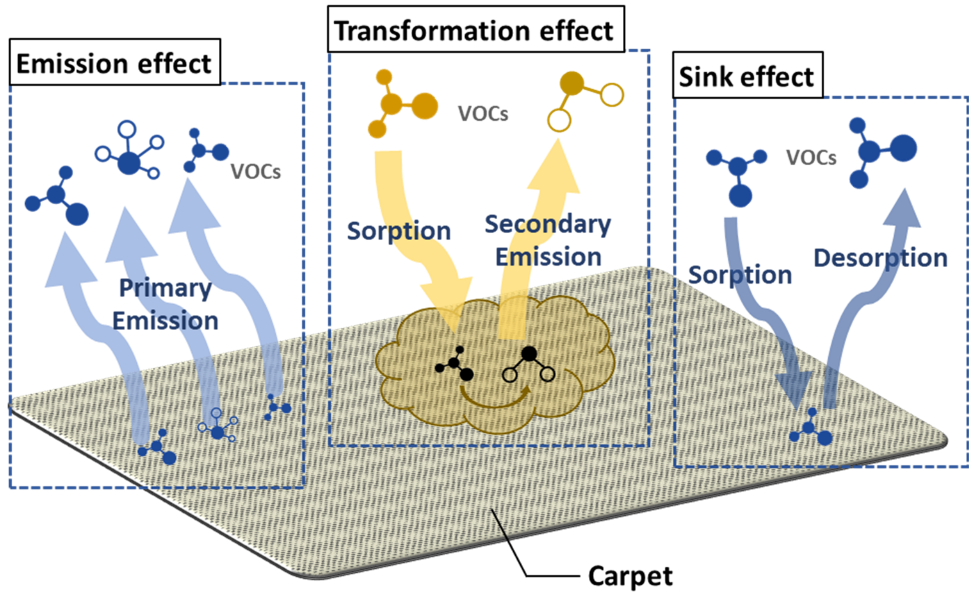

Figure 3. Impact of the carpets on the VOCs concentration in indoor air.

3.1.1. Emission of VOCs with Carpets

This section discusses the source, kind of VOCs, and emission mechanism, as well as relevant parameters affecting the emission rate from carpets. Carpets can emit VOCs, SVOCs, and microbial VOCs (MVOCs). The most emitted pollutants by carpets are VOCs such as 4-phenylcyclohexene (4-PCH, the source of new carpet odour), aromatic compounds (benzene, styrene, toluene, xylenes), and carbonyl compounds. This emission can range from 10 to 10,000 μg m^{-2} h^{-1} [4,28]. Additionally, some SVOCs emitted by carpets are treated by finishing agents, such as per- and polyfluoroalkyl substances (PFAS) from soil retardants [29], organohalogen and organophosphorus from flame retardants [18], triclosan from antimicrobials [30], phthalate esters (PAEs) in plasticizer PVC backing [22,31], p-dichlorobenzene from moth repellent, tetrachloroethene from dry-cleaning agents [32], and silicon composition from water repellent [33].

Moreover, microorganisms can emit MVOCs (especially 1-octen-3-ol and 2-ethyl-1-hexanol) as part of the metabolic processes of microbes. The emission of MVOCs depends on the water content of the carpet, the availability of nutrients, and the presence of oxygen [34]. However, more research is required to better understand when microbial growth occurs and MVOCs are emitted from humid carpets.

There are various measurement methodologies for studying the impact of carpets on IAQ. Practically, the ISO 16,000 series and EN 16,516 are used for sampling, preparation, and measuring the emission of VOCs [35,36]. Nowadays, some voluntary standards are involved in measuring the VOCs emitted by carpets to label carpets with low emission rates. The most applied ones are green labels supported by the Carpet and Rug Institute, the trade association for the North American carpet industry, and Gemeinschaft umweltfreundlicher Teppichboden (GUT), supported by the European textile floor-covering industry. To receive GUT Certification, the emission rates for several VOCs must be less than certain defined rates: the VOCs and SVOCs emissions must be less than 250 $\mu g\ m^{-3}$ and 30 $\mu g\ m^{-3}$, respectively, after three days [37]. Most of these labelling systems use chemical analyses for the measurement of TVOCs, and some specific VOCs and a few, like GUT, use odour tests with trained panels [38,39].

The emission of VOCs from carpets can be categorized as primary and secondary emissions based on the bounding to the carpet. The primary emissions refer to non-bound, or free VOCs of the carpet, such as low molecular weight VOCs used as additives, solvents, and unreacted raw materials like monomers. The secondary emission group comprises emissions of originally physically or chemically bound VOCs of carpet materials. These VOCs are emitted from the carpet by various mechanisms, such as oxidation, decomposition, sorption processes, polymer degradation, maintenance, and microbiological emission (Section 3.1.3). In some cases, describing VOC transfer is complicated due to the impossibility of separating the free VOC from the physically adsorbed VOCs. Significantly, VOCs move freely from adsorbed phase to the gas phase or vice versa to satisfy surface equilibrium due to weak bounding (van der Waal's force) between VOCs and pore surfaces [40]. The primary emissions decrease moderately fast (usually within a year). In contrast, secondary emissions for some building product types, e.g., linoleum, may remain for the entire life of the building product [41].

Two mechanisms reflect the emission rate of VOCs from building materials with no internal chemical reactions: (1) the diffusion of VOCs within the building materials and (2) the evaporation from the building materials' surface to the ambient air. The emission rate may be limited by one or both mechanisms based on the type of building material. In the case of the second mechanism (evaporation), the emission rate of VOCs may be affected by the concentration in the indoor air (equilibrium concentration) [41]. Additionally, the molecular weight of VOCs affects the emission rate as the diffusion coefficient mostly decreases as the molecular weight of the VOCs increases [42].

There are several models available for predicting VOC and SVOC emissions from carpets, such as the first-order decay and dilution models with or without considering the sink effect [42–44]. If the sink effect is considered in the model, a better fit between the predictor variable and the response was found, resulting in higher regression values [44]. However, a more rigorous validation of models is desirable because of the principal assumptions of the model effect on the predicted result of the model. For example, the result of separated fibres and polymer backings of the carpet confirmed that the backing was the most predominant source of emission due to serving as a slow diffusive source of the VOCs. Therefore, the model of these results assumed that the VOCs initiate emission predominantly from a uniform slab of polymer backing material; hence, the researchers claim that this model can predict VOC emissions from new carpets based solely on a knowledge of the physical properties of the relevant compounds and the carpet backing material [42].

Effect of ventilation: Both emission and evaporation mechanisms control the emission rates when the ventilation rate changes. Indeed, a significant impact of the ventilation rate on emission rates was achieved when the ventilation rate was low, but the emission rates become independent of ventilation rates when the ventilation rate is high in both sensory and chemical assessments [45]. For example, Gunnarsen [45] studied the emission from construction products and found that when the low ventilation rate was increased (less than one week), the emission concentration of VOCs from the sources with large surfaces increased. This increase may be caused by an increase in the air velocity above the surface, increasing the mass transfer coefficient and consequently increasing the evaporation of VOCs from the surface [41,45–47].

Effect of temperature: Generally, indoor air temperatures are limited between 17 °C and 28 °C. However, the temperature of the floor covering materials may increase to a higher degree by solar irradiation or floor heating. The VOC emission increases with higher indoor temperatures due to increased diffusion and evaporation of VOC from the surface. For example, the 4-PCH emission from carpets increased when the temperature increased from 23 °C to 50 °C [43,48]. However, increasing the temperature decreases the amount of chemical compounds in carpets as well as the emission rate over time [47–49].

The emission of four finishing materials (carpet, oil-based paint, plywood board, and water-based paint) showed that different air temperatures (23 °C and 30 °C) significantly impacted the chemical emissions, but mainly for the initial emission. For example, after ventilation for two weeks, both the chemical (TVOC) and the sensory emission rate for each material showed no changes in emission between the two temperature levels [50].

Effect of dimensions of a space: Small chambers are typically used to study the influence of different parameters (e.g., temperature, humidity, air exchange rate, air velocity) on emission/sink properties of building materials [51], because in large chambers, the environmental conditions are difficult to control. Additionally, large chambers are cost-intensive, time-consuming, and require complicated test equipment [52]. However, large chambers are more practical in estimating real-life situations for simulating inhabitants' behaviour and sink effects of building materials [51].

Emission of the same carpets in various sizes of chambers with the same air temperature and humidity is ideally expected to demonstrate similar results. However, in some studies, significant differences in the emission isotherm of the carpets in a large chamber (30 m^3) compared to small chambers (0.02, 0.28, and 0.45 m^3) were found [4].

Effect of carpet materials: The material components of carpet layers affect the emission behaviour of carpets. Several studies have been performed on VOC emission of carpets with different material compositions, various fibre piles and backing, the same fibre pile and different backing, and even the same fibre pile and backing. In a study on VOCs emission of 14 carpets with separated layers, emissions from the complete structures were found to be lower than the sum of emissions from the single component layers [53].

A study on the emission from six carpet fibre materials (Triexta (polyester family made by polytrimethylene terephthalate, DuPont), Poly-triexta (75% Polyester, 25% Triexta), polypropylene (PP), polyester, nylon, and wool) showed that VOCs emissions varied significantly as a function of fibre type. Nylon and PP carpets showed the lowest and highest emission of carbonyls, respectively. Formaldehyde (an important harmful agent for human health) emission of Triexta and polyester carpet samples showed the lowest and highest emissions at 3 and 16 $\mu g\ m^{-2}\ h^{-1}$, respectively [54].

The VOC emission from carpets with the same fibre pile can be different when the backing of these carpets are different [53]. For instance, a polyamide carpet with a PVC backing emitted vinyl acetate, acetic acid, 2,2,4-trimethylpentane (isooctane), 2-ethyl-l-hexanol, and 1,2-propanediol (propylene glycol), while the dominant emitted compounds by a polyamide carpet with a polyurethane secondary backing were hexamethylcyclostrisiloxane, 1 butanol, dipropylene glycol methyl ethers (three isomers), and 2,6-di-terf-butyl-4-methylphenol (butylated hydroxytoluene or BHT) [44]. Therefore, it is clear that the carpet's backing affects the type of emitted VOCs [4,42]. Indeed, the VOCs emitted from the backing of a carpet can occur for a long time, and even the air velocity cannot increase the emission rates because the diffusion of the VOCs from the carpet backing is the dominant process [41,42].

For example, 4-PCH is a strong odorant originating from the SBR backing of a new carpet, and the emitted odour may continue for several months [44].

VOC emission from the same fibre pile and backing even disclosed different results. For example, polyamide carpet with SBR latex adhesive backing mainly emitted benzyl alcohol, toluene, and negligible amounts of siloxanes, aldehydes, and aromatics (like 4-PCH), without any emission of the base, acid, and formaldehyde [55], While in another study, it was reported that the primary emission of two polyamide carpets with SBR was styrene, 4-PCH, 4-ethenylcyclohexene, and alkyl benzenes [44]. Further details from experiments and compositions of these carpets need to conclude why there are differences in VOCs emission with the same materials. For instance, it is unclear whether these carpets had the same adhesive glue, weight, and fibre pile thickness. Formaldehyde emission is expected to release unreacted formaldehyde from the adhesive glue for bonding the fibres and the backing of the carpet. One study showed that a wool carpet emitted more formaldehyde and TVOCs than a polyamide carpet and a mixture of wool/polyamide carpet. However, they reported that these results could have been attributed to the backing materials and/or adhesive glues of the carpets [4].

Effect of the preparation of carpet: The differences in VOC emissions varied among the same product types, which reveals apparent differences in manufacturing processes and ingredients [56]. In 1992, four independent variables were examined: oven residence time, latex amount (coating weight), makeup air feeding the drying oven, and type of SBR to produce carpet with low emission. Results revealed that these factors all affect the VOC emissions of new carpets, but it is a very complex phenomenon with uncertainties [13].

Effect of sampling and age of carpet: It is anticipated that variables including the age of the carpet, the type of packaging, and the installation methods influence the emission rate of VOCs. The age of carpets is an important factor because the emission rates of most materials change over time [44]. The primary emission from older carpets can be lower than from new carpets. It has been observed that samples acquired from retailers emitted fewer amounts of VOCs than samples of the same type of materials obtained directly from the factory, suggesting that VOCs are emitted during transport, handling, and storage before installation [56]. The consequence of this finding for research is that sampling and preparation time may influence the emission results, and the age of the carpets may have a role in the inconsistent results across research [54].

3.1.2. Sink Properties of Carpets for VOCs

Research has shown that the sorption potential of carpets may have an impact on IAQ; sorption and desorption of VOCs on materials, are therefore, relevant to consider [57]. However, to test whether 100% of the adsorbed VOCs are re-emitted, long-term desorption data are required to monitor [58].

Carpet materials have been shown to have the largest sorption capacity among different indoor surface materials. Due to their ab/adsorption properties, carpets can reduce indoor air VOC concentrations, but has shown to be followed by re-emission of those VOCs over prolonged periods [59].

Effect of environmental parameters: It has been observed that RH significantly impacts the sorption amount of 2-propanol, a highly soluble VOC. However, no noticeable impact on sorption with increasing the RH was seen for nonpolar VOCs on polyamide and poly olefin carpets [59]. Therefore, it was concluded that RH affects the sorption capacity of VOCs based on the hydrophilicity or hydrophobicity of those VOCs.

In a study, it was found that an increase in temperature and air velocity affected the amount of VOCs adsorbed by ceiling tiles and carpets [12]. In another study, the results of adsorption and desorption of some VOCs in the temperature range of 25–45 °C showed that the adsorption rate decreased more rapidly with increasing temperature than the desorption rate [3]. Additionally, some studies showed that the air velocity and size of chambers did not influence the sorption of VOCs on wool and nylon carpets [57,60].

Moreover, the sink effect of the chamber test can influence the sorption study. To minimise this sink effect, the use of inert materials such as Teflon or glass for chamber walls has been recommended. In addition, results of wool and nylon carpets' sorption studies showed that an experiment conducted with a relatively high loading of VOCs liquid reduced the sink effects of the test chamber and is therefore recommended as well [61].

Effect of type of VOCs: A study on the sorption of toluene and a-pinene by wool and nylon carpets revealed that the sorption was enhanced when both compounds were present in the chamber. The outcome of the experiment was successfully used in the Langmuir model in order to provide a chemical explanation of the adsorption process [62].

Effect of carpet materials: In a study with two nylon carpets from different suppliers, similar sorption capacities were found while the emissions differed. Moreover, another carpet with mainly olefin-based fibres revealed a greater sorption capacity for all VOCs than these two nylon carpets [59].

A study on the sorption effect of carpets comprising of different materials resulted in the following ranking of the sorption capacity for toluene and α-pinene: wool carpet > nylon carpet > PVC coverings > cotton curtain > empty chamber. Additionally, for the wool carpet, it was found that different air velocities (0, 10, and 20 cm/s) did not influence the sorption capacity because of the large surface area of the carpet [57].

Interestingly, carpet (fibres-backing composite) showed the highest sorption for all VOCs in comparison with the sorption capacity of the separated fibres and backing. In addition, this carpet revealed a higher sorption reaction than the sum of fibre + backing sorption, possibly due to the differences in the geometric configurations of the fibre [59]. From these results, it can be concluded that a carpet's structure can impact the carpet's sorption properties, and more studies are required to optimize the effect of the carpet's structure on sorption properties.

As carpets are manufactured with various layers, one study considered the sorption of different VOCs on the fibre pile and backing [59]. The results showed that the polypropylene backing adsorbed significant amounts of VOCs, especially for o-dichlorobenzene and 1,2,4-tri-chlorobenzene, toluene, tetrachloroethene, and ethylbenzene. While the polyamide pile fibres showed that sorption interaction was almost negligible for all chemicals except for 1,2,4-trichlorobenzene [59]. In another study, the wool pile fibre showed more sorption than nylon pile fibre for trichloroethylene. Additionally, nylon fibres absorbed more ethanol than polypropylene or SBR backing [63]. It seems that the difference in the sorption capacity between various pile fibres can be characterized by the hydrophilicity or hydrophobicity properties of fibres and VOCs.

3.1.3. VOC Transformation Reactions with Carpets

As discussed in Section 3.1.1, there are primary emissions from various sources of indoor building materials present in the indoor air. Besides, a building material can release secondary emissions resulting from transformation reactions (like physical, biological, or chemical reactions) [64]. Materials with a large amount of organic compounds, such as carpets, wood, fabrics, and paint, can emit VOCs as secondary emissions [54]. In addition, newer carpets can have higher secondary emissions than older carpets [65]. One study showed that increasing ventilation might result in higher secondary emissions, especially for the material surface with high reactivity to oxidative degradation. Consequently, the secondary emissions, instead of the primary emissions, are expected to impact the perceived IAQ in the long run. It was observed that after a limited decay during the first one or two weeks, the odour intensity remained almost constant during the rest of the experiment period (50 days) [41].

One crucial transformation reaction in the carpet is the chemical reaction between oxidants and materials [64]. Ozone, as an oxidant agent, can react with gas-phase VOC emitted from building materials as well as the organic interface of building materials [40]. The ventilation rate and removal effects of surface interactions with building materials, such as wallpaper, latex paint, carpet, plywood, and plaster, can affect indoor ozone concentrations [66]. Among the building materials studied, carpets reacted significantly with ozone, owing to their high surface area and covering a large fraction of surfaces in the indoor area [14,17]. Ozone reactions with carpet can lead to elevated concentrations of oxidized products (such as aliphatic aldehydes, i.e., formaldehyde, acetaldehyde, and aldehydes with 5–10 carbons), resulting in secondary emissions [66,67].

Reactions among VOCs in an actual indoor environment are the source of short-lived, highly reactive compounds indoors, which makes the investigation of them by physical/chemical analyses difficult. The new reactive products may be readily sensed by occupants but are challenging to identify using standard analytical methods. While, it is possible to study the net effect of a complex VOCs mixture on human perception by sensory evaluation [68]. Therefore, sensory assessments are suitable for identifying variations derived from indoor chemistry, especially for variations missed by the routine analytical methods evaluating indoor air [69]. In this regard, sensory evaluations of ozone removal with building materials (plasterboard, carpet, linoleum, pinewood, and melamine) were conducted to reveal the perceptual effects. Results showed the greatest effect with significantly high odour intensity for carpet when exposed to ozone. Indeed, the compounds emissions from the carpet were transformed to oxidant compounds with negative odour notes caused by the ozone exposure [70].

Nylon carpets with SBR backing were exposed to an ozone environment to investigate the primary and secondary emissions [67]. The carpet backing primarily emitted styrene, 4-ethenylcyclohexene, and 4-PCH, while the nylon fibre emitted C5-C10 aldehydes ~4 times more concentrated than the backing in the presence of ozone. Moreover, in the presence of ozone, benzaldehyde, benzoic acid, and acetophenone reached much higher concentrations in the chamber with the backing material than in the chamber containing the nylon fibres [67].

The research on six carpet fibre materials (Triexta, Poly-triexta, PP, Polyester, Nylon, and Wool) showed that carpets were virtuous sinks for ozone with the potential to diminish ozone levels indoors [54]. The ozone removal percentages and VOC emissions varied significantly as a function of fibre materials. For example, nylon showed to be the least effective at removing ozone from indoor air, while the wool carpet showed the highest percentage of ozone removal and ozone deposition velocity because of the reaction between ozone and functional groups of wool fibre carpet. Additionally, wool carpets showed the lowest molar yield in the formation of secondary carbonyls [54].

It was observed that carpets generally can emit substantial levels of VOCs (secondary emissions) in the presence of ozone [54]. Therefore, to consider the relative IAQ merits, the material composition of carpets for flooring can be selected based on the amount of indoor ozone present. In the case of high concentrations of ozone indoors, the air quality showed to increase when applying wool carpet on the floor. In contrast, nylon showed to be a good option as flooring material in indoor environments that do not have high levels of ambient ozone, while the worst option for flooring material was polyester carpet because of the high emissions of formaldehyde in both indoor environments with and without ozone [54]. Furthermore, secondary emissions from a new carpet may diminish as carpet ages, and ozone removal capacity of a carpet decreases with age because of losing its ability to react with ozone [65,71].

3.2. Particulate Matter

Since people spend most of their time indoors, indoor PMs can significantly affect human health. Indoor particles are either generated from indoor activities, such as the combustion of gas and petroleum-based fuels, smoking, and cooking, or introduced from outdoors via ventilation and infiltration. Resuspension of PM from floorings is an important cause of human exposure, and carpets are a significant reservoir of PM due to their complex structure and high surface area. The following section reviews the behaviour of carpets with regards to deposition and resuspension of PMs.

3.2.1. Particulate Matter Deposition on Carpets

It is known that carpets deposit more particles, dust, and allergens than non-carpet floors and possibly cause worsening of asthma and allergies [72–74]. A study using an isolated room (volume = 14.2 m^3) showed that a carpet contributed to a higher deposition loss rate of particles (<10 μm) under airflow conditions (mean air speed = 5 to 19 cm/s) compared to a bare room [72].

Moreover, the surface of carpets has the potential to support chemical and biological transformations, including particle-bound SVOCs or fungal growth [39]. For example, one study showed that dust presence is an important factor in fungal growth in carpets, and the elevated RH (≥85%) is also an essential variable of increased fungi in carpets [75]. It is also suggested that the material of carpet fibre relates to the potential fungal growth and allergen production, and Olefin fibre showed less fungal and *A. alternata* growth compared to nylon and wool fibres [75].

In addition, a recent study reported the persistence of viruses (MS2 and Phi6 bacteriophages) on carpets for several hours to days, and vacuum cleaning and hot water extraction did not show significant effects in reducing the concentration of viruses [76]. Therefore, understanding the environmental conditions or cleaning methods that reduce the resuspension of deposited particles from carpets is needed to improve IAQ and human health.

3.2.2. Particulate Matter Resuspension from Carpets

Previous experimental studies on particle resuspension from carpets mainly focused on the effects of human activities and indoor RH. Some studies compared the resuspension rate (fraction of a surface species removed per unit time) of particles from carpets to other flooring materials. Various scales of chambers were used in previous studies, and some experiments were conducted using human subjects to simulate resuspending particles by walking. The types of test particles were also different between the experiments, and dust samples from actual building carpets and ISO 12103–1 test dust (Arizona test dust [77]) were mainly used in the previous studies.

Human activities and PM resuspension. The key reason for the resuspension of PM from carpets is human activities such as vacuum cleaning and walking [78,79]. Previous studies showed that the size of PM affects the resuspension mass, and bigger PMs consistently resuspend from carpets more than smaller PMs through human activities. For example, one study showed that PM_{10} has more resuspended than $PM_{2.5}$ during vacuum cleaning [80]. Additionally, the resuspension rate was higher for larger particles (size range of 0.8–10 μm) during walking on loop fibre carpets [81]. Another full-scale chamber study using a walking subject also found a higher resuspension rate for bigger particles [82].

The dominant adhesion and removal forces of particles to carpets vary depending on their sizes. While adhesion forces increase with particle size, the removal forces, such as drag forces of vibration and convection, are proportional to the third and second power of the particle size, respectively [83,84]. Therefore, larger particles more easily resuspend than smaller particles.

Some recent studies focused on particle resuspension and exposure induced by infants' crawling and children's walking. A study that used a robotic infant showed that an infant would receive a nearly four times greater respiratory tract deposited dose of resuspended biological aerosol particles than an adult in terms of per kg body mass [85]. Additionally, the resuspension fractions for infants' crawling (10^{-6}–10^{-1} [-]) are similar to those for adults' walking [86]. Another study used a bipedal robot simulating children's walking and showed that different shoe materials (cotton socks, polyvinyl chloride, and ethylene-vinyl acetate copolymer) produced different sizes and concentrations of particles from carpets [87].

Flooring materials and PM resuspension. In several studies, the resuspension rate of PM between carpets and other hard flooring materials was compared. Generally, carpets resuspend more particles than hard floorings. A new level-loop carpet had a higher resuspension rate than vinyl tile flooring for particle sizes of 1.0–10 μm via walking activity under a ceiling air supply system [81]. Another study that used air jet tubes to simulate vortices induced at the edges of the foot during human walking also reported a higher resuspension rate from nylon carpets than the linoleum surfaces at the same RH levels (10% and 80%) [88]. In addition, the linoleum surface showed significant increases in the resuspension rate of hydrophilic particles as RH decreased from 80% to 10% compared to nylon carpets [88]. Another study that used a mechanical resuspension device to simulate human walking also showed higher resuspension fractions of nylon cut pile carpets than hard floorings (hardwood and vinyl) for particles 3.0–10 μm [89].

In previous studies, it was found that the carpets' surface roughness, fibre resiliency, and electrostatic force may cause a higher resuspension rate of carpets [89]. In addition, low-density carpets resuspend dust more than high-density carpets because of the lower bending resiliency of fibre piles [89]. In contrast, one study reported that a laminate floor resuspended more particles (5 μm and 10 μm) than carpets through vacuum cleaning after several times of simulated walking activities. This result may be related to the surface condition of the test carpets and the positions of embedded particles inside the carpets [79].

Humidity and PM resuspension. Table 1 summarizes the effect of humidity on particle resuspension from carpets in previous experiments. It lists the property of the test carpet, size of the test chamber, PM type, humidity levels, and measured particle resuspension rate.

One experimental study showed that the resuspension rate of PM could be increased and decreased by higher RH depending on the surface condition of the medium-pile carpets (old and new) [90]. Another study showed that increased RH levels (40% and 70%) enhanced dust resuspension from nylon high-density pile carpets, while hard floorings showed decreased resuspension [89]. It is also reported that shaggy carpets did not show an obvious influence of different RH (40, 60, and 80%) on the mass concentration of particles with diameters between 0 and 5.0 μm but showed an influence on the mass concentration of particles with diameters between 5.0 and 10.0 μm [91]. This result may be affected by condensing of fine particles due to humidity.

The RH levels affect the electrostatic and capillary forces of particles. In high humidity conditions, the capillary force will be increased by forming meniscuses between particles and surface asperities, and the adhesion force will be increased. Additionally, higher RH increases cohesive forces between the particles and helps to form an agglomerate, resulting in the reducing resuspension due to the presence and strength of the particle clusters [89]. Moreover, the adhesion force by electrostatics was thought to decrease with higher RH because the extra water increases the leak-off rates of charges on particles, resulting in a reduction of adhesion forces and prevention of charge accumulation [89]. However, the results of Tian et al. [89] showed that the difference in surface materials caused differences in the impacts of the capillary and electrostatic forces on particles' adhesion forces in the different RH conditions. Thus, the effect of RH on PM resuspension can differ depending on the material type and surface condition of carpets.

The previous studies also showed that the effect of indoor RH on the resuspension of PM from carpets is related to the type of particles. A recent study examined the effect of humidity on the resuspension of biological particles from nylon carpets and linoleum [88]. While hydrophilic particles (quartz and dust mite) showed an increased resuspension rate as RH decreased from 80% to 10%, the resuspension rate of hydrophobic particles (cat and dog fur) did not show a significant effect of RH. The hydrophilic particles may make water films under high humidity conditions by absorbing moisture. The water film may reduce particles' resuspension by increasing the particles' adhesion force and decreasing the potential for electrostatic repulsion.

Table 1. Effect of humidity on particle resuspension from carpets in previous experiments.

Ref	Test Materials	Test Chamber	PM Type	RH	Resuspension Rate	Major Results about RH Effects
[81]	• New and old level-loop carpets • Vinyl tile	Full-scale experimental chamber (4.88 × 3.66 × 3.05 m)	ISO 12103–1 Test dust (A1) (0.8–10 µm)	30–50%	1.7×10^{-7}–1.7×10^{-4} min^{-1}	• The individual variability of simulated walking outweighed the effect of the difference in humidity levels.
[90]	• Medium-pile dirty carpet (8 mm nylon fibre) • Medium-pile clean carpet (10 mm nylon fibre)	Chamber (7.0 × 4.0 × 6.5 m)	ISO 12103–1 Test dust (A1) (0.8–10 µm)	20, 40, 80%	5.0×10^{-6}–4.0×10^{-2} mg/mg (Emission Factor)	• High RH enhanced resuspension from new carpets, but it has the opposite effect with old carpets.
[89]	• High and low-density cut pile carpets • High-density loop carpet • Hardwood • Vinyl	Chamber (61× 38 × 53 cm)	Dust in 18 houses (0.4–10 µm)	40% and 70%	1.5×10^{-6}–1.5×10^{-3} min^{-1}	• Flooring type was the most influential on PM resuspension compared with RH and surface dust loading. • Increased RH enhanced resuspension on high-density cut pile carpet, whereas the opposite effect was observed on hard floorings.
[88]	• Carpet (nylon) • Linoleum	Chamber (40 × 20 × 20 cm)	Quartz, dust mite, cat fur, dog fur, and bacterial spore (1–20 µm)	10, 45, 80%	1.0×10^{-9}–1.5×10^{-4} min^{-1}	• Resuspension rates of hydrophilic dust mite particles increase as RH decreases from 80% to 10%. • Resuspension rates of hydrophobic cat and dog fur particles are within the measurement error range of over 10–80% RH.
[91]	• Shaggy carpet • Low-level loop pile carpet (polyester) • Hardwood flooring	Laboratory room (6 × 3.6 × 3.5 m)	ISO 12103–1 Test dust (A1) (0–10 µm)	40, 60, 80%	0–1.2×10^{-9} min^{-1}	• With the increase of RH, the resuspension rate of fine PMs decreased.

4. Conclusions and Recommendations for Future Studies

Carpets are one of the elements in buildings that cover a large floor area of indoor spaces and can have a major impact on indoor air quality (IAQ) because of their multiple layers of material and high surface area of dense fibre piles. This review seeks to summarize the current understanding of how carpet affects indoor volatile organic compound (VOC) concentrations and particulate matter (PM) distributions. The following main findings can be concluded:

- In real situations, the effects of carpets on IAQ are complicated because carpets affect the emission, sink, and transformation of VOCs. Previous studies showed that each layer of a carpet (fibre pile, backing, and adhesive) influences these behaviours.
- Carpets with separated layers showed that VOC emissions from the complete structures were lower than the sum of emissions from the single component layer, while

the sorption was possibly higher due to the differences in the geometric configurations of the fibre.

- Carpets work as sorption sites with the ability to reduce peak concentrations of indoor VOCs and re-emit them over prolonged periods. Indoor environmental parameters such as RH affect the carpets' sorption capacity of VOCs depending on the molecules' hydrophilicity or hydrophobicity.
- In general, carpets resuspend more particles than hard floorings, and bigger PMs resuspend from carpets more than smaller PMs through human activities. In addition, the effects of RH on PM resuspension depend on the surface conditions of carpets, particle size, and particle types (hydrophilic or hydrophobic).

While the impact of the carpets on IAQ is well documented in laboratory studies, the effect of carpets on indoor air in real-life settings like living spaces and workplaces requires further investigations to clarify the full capacity of carpets. To better understand how carpets influence VOCs concentrations in actual indoor environments, future studies are needed to evaluate the carpets' sorption capacity of VOCs emitted from different building materials or human activities and measure re-emissions over long times. This risk and benefit of carpets on the sorption of VOCs demonstrates the effects of carpets on IAQ. For example, VOCs can be absorbed when a source is present and be re-emitted when the source is gone; or absorbed when windows are closed (no ventilation) and desorbed when windows are opened, in the case of a permanent source. In addition, more studies are needed to clarify the proportion of each layer in carpets' behaviour regarding IAQ. The results of these experiments could lead to more knowledge on the material needed for each layer to improve the positive impact of carpets on IAQ.

With regards to research on PM, synthetic fibre carpets (e.g., nylon, polypropylene, polyester) were mainly used in previous studies, and the difference between natural and synthetic fibre carpets on particle deposition and resuspension has not been investigated. In addition, previous experiments mainly examined the resuspension rate of particles caused by simulated temporary human activities. The long-time effect of carpets on airborne particle concentration and inhalation exposures is still unclear, and an analysis of the daily human exposure and health effect is required.

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