3-2020

Ten Questions Concerning the Implications of Carpet on Indoor Chemistry and Microbiology

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Citation Details

Haines, S. R., Adams, R. I., Boor, B. E., Bruton, T. A., Downey, J., Ferro, A. R., ... & Jacobs, D. E. (2020). Ten questions concerning the implications of carpet on indoor chemistry and microbiology. Building and Environment, 170, 106589.

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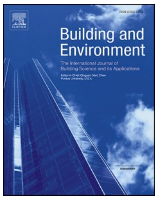
Building and Environment 170 (2020) 106589

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv



Ten questions concerning the implications of carpet on indoor chemistry and microbiology

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ARTICLE INFO

Keywords:
Carpet
Flooring
Dust
Resuspension
Indoor microbiology
Indoor chemistry

ABSTRACT

Carpet and rugs currently represent about half of the United States flooring market and offer many benefits as a flooring type. How carpets influence our exposure to both microorganisms and chemicals in indoor environments has important health implications but is not well understood. The goal of this manuscript is to consolidate what is known about how carpet impacts indoor chemistry and microbiology, as well as to identify the important research gaps that remain. After describing the current use of carpet indoors, questions focus on five specific areas: 1) indoor chemistry, 2) indoor microbiology, 3) resuspension and exposure, 4) current practices and future needs, and 5) sustainability. Overall, it is clear that carpet can influence our exposures to particles and volatile

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https://doi.org/10.1016/j.buildenv.2019.106589
Received 30 September 2019; Received in revised form 19 November 2019; Accepted 7 December 2019
Available online 18 December 2019

compounds in the indoor environment by acting as a direct source, as a reservoir of environmental contaminants, and as a surface supporting chemical and biological transformations. However, the health implications of these processes are not well known, nor how cleaning practices could be optimized to minimize potential negative impacts. Current standards and recommendations focus largely on carpets as a primary source of chemicals and on limiting moisture that would support microbial growth. Future research should consider enhancing knowledge related to the impact of carpet in the indoor environment and how we might improve the design and maintenance of this common material to reduce our exposure to harmful contaminants while retaining the benefits to consumers.

1. Introduction

Carpet constitutes about half of flooring in the United States and is thus prevalent in the indoor environment [1]. Carpet can benefit an indoor space through sound reduction, aesthetics, comfort (both softness and temperature under foot), and injury prevention. It has also received higher comfort ratings compared to solid floors like concrete [2], and in occupational settings, workers who spend 10% of their time standing on hard surface floors compared to soft floors have a 30% increased risk of developing plantar fasciitis [3]. At the same time, use of this material influences indoor environmental quality through impacts on gas-phase air pollutants and particulate matter, including microbiological and chemical components. For example, the mass loading of dust is generally greater in carpets than a comparable area of hardwood floors [4]. The resuspension of particles containing microbes following the physical disturbance of carpets is an important source of human exposure to indoor particles [5,6]. The prevalence of this flooring material dictates the need to better understand the implications of its use in the indoor environment and on sustainability. In this manuscript, we explore questions about the use of carpet related to five general topics: (1) chemistry, (2) microbiology, (3) resuspension and exposure, (4) standards and guidelines, and (5) sustainability (Fig. 1). This report is the result of the workshop “Implications of Carpets on Indoor Chemistry and Microbiology” held on July 30–31, 2019, at The Ohio State University.

2. Ten questions

2.1. Q1: What materials are used to make carpets, why are carpets used, and what is carpet’s share of the flooring market?

Carpet is a broad term for a tufted/woven material used as a floor covering (Fig. 2). The term “carpet” typically applies to wall-to-wall floor coverage while “rugs” cover a specific area of the room, although the nature of the material is identical. Current manufacturing practices produce carpets of diverse composition. Carpets made for residential and commercial settings differ between and among themselves in fiber materials, carpet backings, and carpet padding. Of all carpet, over 95% is made of synthetic fibers, including nylon, polyester and olefin [7–10], and the remainder include natural fibers such as wool. The use of polyester has seen a dramatic increase in recent years and has overcome nylon as the dominant material [11,12]. Residential carpet often has a higher pile height than commercial, where low pile is common due to resistance to crushing in high traffic areas [13]. The tufted/woven loops can remain looped (so-called loop pile), or they can be cut to create vertical strands (so-called cut pile, as in Fig. 2). Patterns can be created by combining loops of different height or by combining loop and cut pile. Carpet density can also be manipulated by changing how closely the different fibers are tufted into the carpet backing. Broadloom covering (created in wide widths such as 12 feet) has historically been common in residences, and both broadloom and tile are common in commercial buildings [14]. Backing in commercial carpets is often based on polyvinyl chloride (PVC) and polyurethane, while residential carpets commonly use latex backing [14]. Carpet padding may be made of fiber, sponge rubber, or urethane foam. Fiber carpet padding, which has a firm feel, could be natural (e.g., animal hair, jute), synthetic (e.g., nylon, olefin), or resonated recycled textile fiber. Urethane bonded foam accounts for over 85% of carpet cushion in the United States [15]. The use of carpet pad underlayment is typical of residential installations, while the use of adhesives for installation predominates in commercial settings.

Common factors for selecting carpet as a flooring material may include sound dampening, comfort under foot (including softness and thermal response), injury prevention, aesthetic preferences, stain resistance, strength, durability, and cost. Within the United States, carpet and rugs make up about 54% of the flooring market [16], which is down from 66.9% a decade ago [17]. This downward trend is often attributed to the growing hard surface flooring market, though rug sales have grown with an increase in popularity of hard surface flooring [17].

2.2. Q2: How does carpet influence indoor chemistry?

Carpets can influence indoor chemistry through several mechanisms: as a primary source of chemical emissions, as a reservoir for the uptake and re-emission of chemicals (sorption/desorption), and as a medium that supports transformations among indoor chemicals, such as oxidation, hydrolysis, and acid-base reactions.

2.2.1. Carpets as sources of chemicals in the indoor environment

Carpets act as a primary source of volatile organic compounds (VOCs) to the indoor environment [18]. The term primary refers to chemicals that are present in the material when installed and are then released indoors, and thus primary emissions are present from most building materials. Many studies have contributed to our understanding that hundreds of VOCs and semi-volatile organic compounds (SVOCs) are emitted from carpet, underlayment, and adhesives [19–25]. Some identified VOCs include 4-phenylcyclohexene (4-PCH, the source of new carpet smell), aromatic compounds (styrene, benzene, toluene, xylenes), and formaldehyde [24,26]. Primary emissions from carpet can impact overall indoor VOC levels [27], and can contribute adversely to sensory evaluations of indoor spaces compared to other indoor building materials [28]. Studies of carpets report emission factors or concentrations of specific or total VOCs (TVOC) resulting from carpet pile or backings and adhesives that range over several orders of magnitude; various studies report emission factor ranges that span 10–10000 $\mu g\ m^{-2}\ h^{-1}$ [24,29].

Numerous SVOCs are (or have been) used in the manufacture of carpets. For example, some compounds include fluorinated soil retardants such as per- and polyfluoroalkyl substances (PFAS) [30,31], antimicrobials such as triclosan [32], and phthalate plasticizers, which may either be in the dust or could result from PVC used as backing in commercial applications [14,33]. Organohalogen and organophosphorus flame retardants are present, as contaminants, in bonded carpet padding made of recycled polyurethane furniture foam [34]. Of these SVOCs, PFAS are perhaps the most studied, and correlations have been observed between the presence or amount of carpet in buildings and concentrations of PFAS in dust [35] and on interior surfaces [36]. PFAS are currently being phased out of construction of new carpets, but turnover of installed carpet and stock of carpet in stores can take years, if not decades.

In addition to chemicals that are part of the carpet material, after-

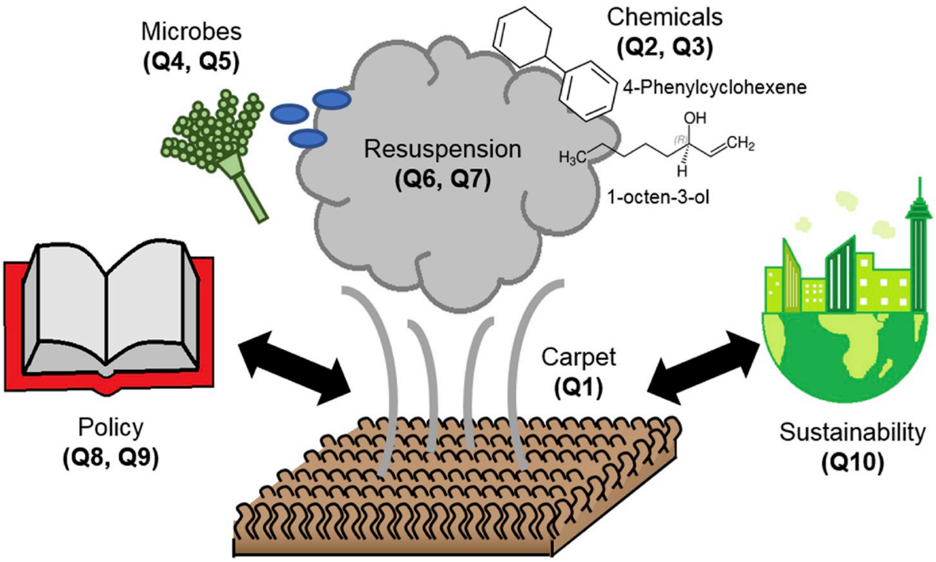

Fig. 1. Carpet has important implications for indoor microbiology, indoor chemistry, human exposure from dust resuspension, guidelines/standards, and environmental sustainability. The question(s) that discuss each of these topics are indicated on the figure.

market application of products can introduce chemicals into the indoor environment through the carpet matrix. For example, carpet cleaning and pest control practices result in the application of chemicals to carpet. In one noteworthy example, frequent application of after-market stain-protector by a family was shown to lead to elevated concentrations of perfluorohexane sulfonate (PFHxS) in carpet, dust, and blood serum of the residents [37].

2.2.2. *Carpets as sorptive/desorptive surfaces*

Carpets have substantial surface area that can increase chemical surface reactivity. Carpets may cover an entire building floor area, and the presence of fleecy, porous mats comprised of small diameter textile fibers greatly increases material surface area compared to that of estimates via aerial projections of the material. Estimates of indoor surface area to volume ratio are approximately 300 times greater surface area per unit volume in indoor than outdoor environments [38]. Note these estimates do not consider the complex geometry of materials like carpets; indoor surface area to volume ratios that included carpet fiber and pore area would be substantially greater than estimates that consider only floor area.

Carpet surfaces impact indoor chemistry through reactive uptake, sorption/desorption, and particle deposition processes. Sorption and desorption of VOCs and SVOCs can alter indoor air chemistry by 1) attenuating peak concentrations of an emission event that emits air pollution into the indoor space and 2) prolonging exposure to the event through subsequent exposure after re-emission [39–41].

The relative importance of the attenuation vs. re-emission phases of these sorption/desorption processes depend on the specific sorbent/sorbate interaction and the environmental conditions. At equilibrium, the sorption capacity of carpets appears to be inversely correlated to the VOC vapor pressure [39,42,43], and for some carpet-VOC combinations, sorptive processes may be relatively unimportant. However, in residential buildings where the outdoor air ventilation rate is often low, the VOC removal rate from sorption to carpets can be comparable in magnitude to the removal rate from ventilation [41,44,45] and can be relatively higher than removal rates from other building materials and furnishings [46–48] due to its greater normalized surface area [49,50]. In one study comparing wool carpet, nylon carpet and polyvinyl chloride

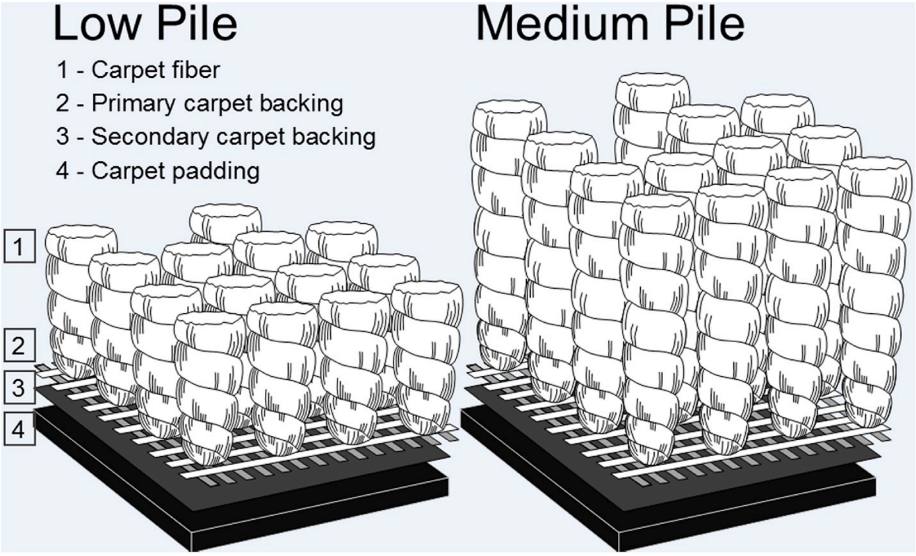

Fig. 2. Structure of an example cut pile carpet.

(PVC) coverings, adsorption of α-pinene was higher in both carpet types than the PVC coverings [46]. Carpet padding tends to contribute more to sorptive interactions with VOCs than other components of the carpet system [39]. Several models have been developed to simulate the sorption process of VOCs to carpet [43,45,48,51–54]. A wide range of SVOCs sorb effectively to clothing textiles, and by extension, to carpet textiles [55,56]. Carpets are known to be a strong sink for low volatility compounds such as nicotine and phenanthrene [47,57], organophosphorus flame retardants [57], as well as phthalates and adipates [58]. These SVOCs may then be slowly re-emitted from carpets to the indoor space over periods of years or more, perhaps for the remaining life of the carpet.

In addition to specific sorbent/sorbate interactions, environmental conditions also affect the sorption/desorption processes. Indoor relative humidity (RH) can significantly influence the degree of sorption for soluble VOCs due to absorption into the condensed water within the porous carpet fiber media [39]. Also, at elevated relative humidities (>80%), elevated concentrations of common indoor gases, such as CO_2 and NH_3, can influence the VOC sorption capacity of carpet [59]. Along with RH, temperature can affect the extent of VOC sorption to carpet. Temperature is expected to affect the gas-carpet equilibrium partitioning in a manner analogous to its effect on gas-particle partitioning [49]. The change of room temperature can lead to the redistribution of organic vapor between the bulk air and indoor surfaces, such as carpets.

2.2.3. Carpets as surfaces for chemical transformations

Carpets interact with oxidants in indoor spaces, through reactive uptake processes [60] where carpet materials or compounds stored in the carpet are oxidized by reactive indoor air pollutants. Most extensively studied to date is the interaction of carpet with ozone. The removal effect of carpet on indoor ozone can be substantial: a wall-to-wall carpeted room provides an ozone scavenging effect equivalent to ~0.4 air changes per hour (ACH) of airflow through an efficient ozone-scavenging filter [50]. Hard floors are generally much less reactive with ozone, though unglazed tile floors can have comparable uptake of ozone to that of carpet [61]. For comparison, a similar scaling calculation to that performed by Morrison and Nazaroff [50], using ozone deposition velocities for two types of bamboo flooring (0.04, 0.11 m/h), ceramic tiles (0.14 m/h), and linoleum (0.25 m/h) [62,63], show that these hard flooring materials provide ozone scavenging equivalent to ~0.01–0.1 ACH. While the greater ozone removal effect to carpet serves to reduce indoor oxidant levels, ozone reactions with carpets also contributes to the production of secondary byproducts [64,65]. An early study of carpets, ozone, and VOCs [64], found that ozone-carpet interactions resulted in the formation of carbonyl compounds, including formaldehyde, acetaldehyde, and C5-10 aldehydes. Spinning oil residue on carpet fibers may be responsible for these secondary oxidation products for new carpet [65]. Since this study, the sink effect of ozone for carpets and the resulting byproduct formation has been extensively studied. Carpet remains an efficient ozone scavenger and producer of carbonyls under varying carpet type, temperatures, relative humidities, and airflow conditions [50,65–70]. Over time, reactive coatings on carpet may become depleted, thus reducing ozone uptake rates and secondary emission rates [71].

2.3. Q3: What more should we know about how carpet influences indoor chemistry?

We need to continue to refine our understanding of chemical emissions from carpets into the indoor environment, especially for emerging contaminants. We also need to better understand the chemical reactions occurring on the carpet, including aqueous reactions in water films on porous indoor surfaces. Additionally, work measuring VOC emissions from carpet to characterize new materials and manufacturing processes as they are introduced into the market will continue to be important.

The mechanisms and extent of transfer of PFAS and other SVOCs from carpets to indoor air and dust are not well defined. Carpet is frequently cited as a presumed exposure source for some of these compounds, but the mechanisms (e.g. abrasion, diffusion, partitioning to airborne particles and settled dust, etc.) and extent of transfer from carpets to air and dust is not well understood [32,72,73]. Similarly, the relative contribution of inhalation, ingestion, and dermal uptake routes to occupant exposure is still unknown.

Studies investigating the mechanisms and impacts of carpet-oxidant interactions beyond ozone are needed. The importance of heterogeneous chemistry in impacting levels of reactive nitrogen species in outdoor atmospheres [74] compels further investigation of carpet as a high surface area material that may impact levels of reactive nitrogen species indoors. Several studies report nitrogen dioxide (NO_2) deposition rates to carpets and show evidence for the formation of nitrous acid (HONO) due to the interaction of NO_2 and surface-sorbed water on carpet [63,74–76]. The studies note that the ability of a surface to sorb water may drive longer-term HONO release after an NO_2 injection event. A recent field study in a residence appears to confirm this, indicating indoor HONO levels are driven by gas-surface equilibrium [77]; though flooring type was not indicated, carpets are a porous material that can absorb water during high air humidity conditions. A recent study also points to the potential for HONO production from indoor surfaces to be impacted by the presence of cleaning products [78]. Given that indoor nitrous acid is both a direct health concern and an important source of the hydroxyl radical (•OH) indoors [79], further study into the role of carpets in influencing indoor HONO and reactive nitrogen species is warranted.

Research into HONO implies accumulation of chemicals in or on carpets may have broader impacts on indoor chemistry. This sink effect, where carpets accumulate VOCs, SVOCs, and particles [80,81], de-couples sorbed chemicals from air exchange, enabling longer indoor residence times and more opportunity for chemistry to occur. In other words, by holding greater amounts of dust and surface-sorbed compounds compared to other flooring materials, carpets might serve as a facilitator of indoor chemistry by “storing” chemicals for future reactions. These chemicals stored in carpets may become available for interaction with short-lived indoor oxidants that are present only under specific or transient conditions [82]. The rate of reaction of oxidants with surface-sorbed chemicals has been shown to be hundreds of times greater than that of gas-phase chemistry [82–84], and reaction products and yields may differ between the two [85]. Reaction sites on carpets are also affected by acid-base chemistry [59].

Due to the presence of esters in carpet materials and adhesives, more attention should be given to the possibility of hydrolysis reactions. Humidity and the presence of an alkaline surface, such as concrete, can promote hydrolysis of esters, thereby generating smaller, more volatile species. Hydrolysis of di-2-ethylhexyl phthalate (DEHP) is thought to be a dominant source of 2-ethyl-1-hexanol (2 EH) indoors [86], which is an irritant even at relatively low concentrations. Emissions of 2 EH increased when carpet was attached to flooring with a high water content, using a phthalate containing adhesive [87]. The use of PVC (which contains the plasticizer DEHP) as a carpet adhesive is no longer common. However, DEHP originating from other sources may be present in carpet dust [88,89]. Apart from the well-known microbial and corrosion concerns associated with moisture, this emphasizes how crucial moisture issues are in the built environment.

2.4. Q4: How does carpet influence microbiology and the presence of other biological agents in the indoor environment?

The main routes by which carpets influence indoor microbiology are by 1) accumulating microorganisms and microbial products as part of the dust milieu and 2) potentially creating an environment that is conducive for biological proliferation. Biological agents in house dust can be an important component of building-associated exposures that elicit both protective [90,91] and detrimental [92] health responses in occupants.

Biological components of dust are theoretically as diverse as the complex ecology of outdoor environments, and include microorganisms (bacteria, fungi, algae, protista) as well as pollen, dust mites, pet dander, and arthropods [93–97]. Most research on the biology of indoor environments has focused on either allergens or microorganisms, predominantly fungi. Next-generation sequence-based technology applied to indoor environments has revealed that the fungal communities within carpet dust reservoirs are composed of a vast array of fungi, representing a much more diverse pool than previously estimated when using traditional exposure assessment methods [98–100]. Previously overlooked fungi include many yeast species, including *Cryptococcus*, and outdoor-derived fungi, such as plant-pathogenic rusts [98,100]. Because the mass of dust is greater per unit area of carpet than it is for hard, smooth surfaces [4][see Question 6], the presence of carpet increases the potential for our exposures to these biological agents. Additionally, the presence of carpet may alter the microbial concentration in dust on a per dust mass basis. Most studies have shown that concentrations of endotoxin and 1-3-beta-d-glucan per gram of dust are higher in carpet dust compared to dust from other flooring types [101–105], but one study observed the opposite result [106]. Culturable fungi were also found to be higher in dust from carpeted floors [107].

2.4.1. Moisture and microbial growth

Additionally, carpets may create conditions hospitable to microbial growth and dust mites, mainly through increased moisture content [107,108]. Research done, typically in the context of dust mites, conveyed that carpets can show RHs higher than the surrounding environment [94,109,110]. The three-dimensional, fibrous nature of carpet laying on the ground can create thermodynamic conditions that promote the retention of water. For example, Cunningham et al. (1998) identified a gradient in RH that increased from the top of the carpet in contact with room air to the base of the carpet. This RH gradient is related to temperature gradients in the carpet, while absolute humidity was the same in room air, on the top of the carpet and at the base of the carpet [110]. The carpet showed a dampened response to changing RH values compared to the room air. While the RH in the base of carpet hovered around 70%, the RH of the room air fluctuated between 50 and 75% RH. In addition to retaining moisture from the ambient air in the room, in buildings with defective design or construction elements, carpets can also encounter moisture due to leaks from waterproofing installation issues, plumbing or the ground below [111]. Water from the soil or cement foundation, for example, can migrate to the floor surface [112]. This water can moisten carpet surfaces, as is commonly observed in carpeted basements.

Beyond the simple parameter of growth [113], the moisture condition in carpet has also been found to influence the type of microbial genes that are expressed. Chamber experiments of dust embedded in carpet and incubated at various water activities (a_w) revealed systemic changes in fungal gene expression between fungi grown at a water activity of either 0.85 or 0.5 and 1.0 a_w. At 1.0 a_w the up-regulation of many allergen-encoding genes, general pathogenicity pathways, mycotoxins, and secondary metabolites occurred [114]. Mycotoxins are non-volatile secondary fungal metabolites capable of causing negative health effects [115], and are also influenced by the RH and a_w at which microorganisms grow [116–118]. Some mycotoxins have been identified in carpet and indoor dust [119–121], but the related health effects of this exposure are still unclear. For example, the production of aflatoxin, a type of mycotoxin, increased when *Aspergillus flavus* was grown at a water activity of 0.99 compared to 0.93 [116], and production of ochratoxin, another type of mycotoxin, increased in both *Aspergillus carbonarius* and *Aspergillus niger* at water activities of 0.95–0.98 compared to a water activity of 0.92 [118]. The increase in mycotoxin production was accompanied by an increase in mycotoxin-related gene expression both in pure culture [116] and in a mixed culture of fungi isolated from house dust [114,116]. If the water activity of the dust in the carpet were to reach these high levels, we may see this type of gene expression or mycotoxin production. It should be noted however, that in a well-designed, constructed and operated building these levels of water activity typically would not be encountered.

2.4.2. Carpet cleaning and decontamination

Indoor house dust is a heterogeneous mixture that contains both inorganic and organic materials and varying particles sizes [122]. Vacuuming carpets does remove biological agents (as well as dust in general), but the methods used in academic studies are likely much more rigorous than typically used in homes. In a laboratory-based study, dust was artificially embedded on different flooring types in order to test the removal efficiency of vacuum cleaners [123]. The results showed that most of the dust was collected during the first ten vacuuming cycles, where a vacuuming cycle was 5 min on a 0.63 m^2 carpet. After 60 vacuuming cycles, 90% of embedded dust was found in the vacuum cleaner bag when using the rotating brush on the bottom of the vacuum, whereas only 75% when using a plain nozzle in the vacuum cleaner. One study found about 50% of the fungi, dust mites and dust allergens were removed from carpet when vacuumed by 4 passes at a rate of 55 cm/s [124]. Vacuuming at a rate of 0.5–1 min/m^2, depending on the floor type, resulted in a steady state quantity of dust removed after six cleanings [125]. Another study found that it took vacuuming 6–45 min/m^2 to remove deep dust loading from older carpets [126].

Lastly, carpets have demonstrated resistance to decontamination processes following an accidental or intentional release of spore-based biological agents such as *Bacillus anthracis*. The characteristics of carpet make it difficult to decontaminate using wipe methods due to the penetration of spores deep into the carpet matrix. Even immersion of carpet in pH-adjusted bleach (a mixture of household bleach, water, and acetic acid [vinegar]), a combination that has been shown to be highly effective in the sporicidal decontamination of biological threat agents like *Bacillus anthracis*, for up to 60 min, did not achieve the 6-Log reduction generally desired for biological decontamination [127].

2.5. Q5: What more should we know about how carpet influences indoor microbiology?

We need more fundamental information on how the presence of carpet changes microbial communities, microbial function, and microbial exposure in indoor environments – both in comparing carpets to other flooring types, and between different types of carpets. We then need to understand the implications of changes to microbial exposure on human health.

First, we need to better understand the water availability to microbes in carpet. The mechanism that yields available water for microbes in carpet and other indoor surfaces – apart from super-saturated RH conditions (e.g., a hot shower inducing condensation on bathroom walls) – remains unclear. It is also not well known how often elevated RH conditions occur under realistic building scenarios. Cunningham et al. (2004) developed a model to predict equilibrium RH (ERH) at indoor surfaces, but this model does not describe the water that may be available for microbes on the surfaces, which is a key factor for their growth [128]. To our knowledge, the only published study that relates ERH and dust moisture content is a thesis document [129], which draws upon insights from the aerosol science community, where there have been considerable efforts to understand how ambient dust particles interact with atmospheric water [130,131]. Understanding the nature and intensity of water uptake is critical for predictions of microbial growth, as it enables the linkage between indoor RH and the time-of-wetness model for carpet. Given the shift to newer polyester-based carpets, it is similarly important to understand how different carpet materials behave when subjected to different moisture conditions. Additionally, we need to understand the efficacy of antimicrobial coatings and consider their use in a risk-benefit analysis.

Likewise, we also need to understand whether and how the microbial portion of dust is altered depending on the matrix in which it is found. For example, little is known about how the microbial components of dust on a non-porous, hard surface, such as hardwood floors, changes over time relative to dust embedded in a carpet; similarly, how the dust changes within carpet made of different materials is not known.

Currently, there is a dearth of studies that have examined the association between allergy/asthma symptom reduction in homes with or without carpet. Some studies have indicated that carpet may contribute to adverse health effects for individuals with asthma and allergies [6, 132–137]. Carpets can serve as a reservoir for inhalant allergens from not only fungi, but dust mites, pets, rodents, cockroaches and other plants and animals [138]. Carpet removal interventions have been shown to be effective at lowering asthma prevalence when combined with other allergen reduction measures [139,140]. Understanding the specific effect of carpet may be a fruitful area for further research.

Certain studies have not been able to detect a significant difference in exposure to carpet and asthma symptom reduction [141,142], though the homes in the Morgan et al. inner city asthma study (ICAS) did have a low prevalence of carpet [143]. Another study found that fewer asthma symptoms were associated with carpet or rugs in bedrooms. However, this association most likely resulted from highly symptomatic asthmatic individuals previously removing the carpet in their bedrooms due to medical advice [144], which has also been demonstrated elsewhere [145]. An alternative speculative explanation for this association is that carpet in the bedrooms helps to prevent allergens from entering the bed by removing particles tracked-in on feet, such as cockroach allergen from kitchens, but this needs additional research [146].

Lastly, we need efforts to develop a robust definition of a “healthy” indoor microbiome [147]. This should include a definition of what species are present, but also how this impacts chemistry. Carpet microbiomes can interact with phthalates in carpet [148], but it is unclear what other chemical interactions can occur between the hundreds of chemicals and thousands of microbes present. Generally, studies have focused on fungal growth from carpets exposed to high moisture [113], but research exploring the slow growth processes by fungi (including yeasts) and bacteria tolerating lower water activities may offer further insights [149]. Additionally, we need to understand how different carpet types and dust loadings influence microbial communities [150]. We need to build upon existing knowledge of how carpet influences health [6] by studying how carpet, compared to other flooring types, affects human health through immunomodulatory stimulation, allergenic, toxicological and other combined synergistic and antagonistic effects.

2.6. Q6: What do we know about resuspension and implications for exposure in relation to biological and chemical agents?

Particle resuspension from flooring occurs due to human activity. For most published studies, resuspension of coarse-mode particles (particles with diameters > 2.5 μm) has been found to be higher from carpet compared to solid flooring [6,151]. The resuspension of dust from carpet has important implications for human exposure to microbes, chemicals, and allergens.

2.6.1. Carpets are reservoirs that act as both a source and a sink for indoor dust

Human-driven resuspension from carpets and hard flooring can be a significant indoor emission source of coarse-mode biological and abiotic particles in the indoor environment. An adult walking across the floor can resuspend 10–100 million particles per minute [152], many of which are likely to be of biological origin [153]. PM_{10} (all particles smaller than 10 μm) mass emission rates can exceed 10 mg per minute [154]. Walking-induced resuspension can be the dominant source of biological particles indoors, accounting for more than two-thirds of biological particle emissions [155,156]. Besides walking, vacuuming can induce the resuspension of PM_{10}, including airborne allergens, from carpets and hard flooring [151,157,158]. For the vacuum cleaner tested, approximately half of the resuspended mass during vacuuming might be attributable to walking on carpet [158]. Thus, resuspension may contribute meaningfully to our inhalation exposures to the microbial and allergenic content of carpet dust and can be influenced by the style of human movement across the floor, with bacterial and fungal levels 8- to 21- fold higher for crawling infants than walking adults [159].

Most studies have found that carpets resuspend more particles than hard flooring during human walking under typical building conditions due to both a higher typical dust loading and a higher resuspension fraction. Carpets tend to have higher floor loading of particles, that is, the mass of particles per area of flooring is higher in carpets [4,160]. Also, carpets have a higher resuspension fraction (the fraction of particles on the surface that resuspend) compared to hard surfaces under a typical range of dust loadings, as demonstrated by nearly all studies that have compared resuspension fractions of carpets and hard flooring during walking, even when the floor loading of particles is the same [152,154,157,161,162]. One peer-reviewed study has found increased resuspension from hard flooring compared to carpet for 0.8–1.5 μm particles, with a relatively high dust loading of 18 g/m^2, but larger particle sizes were not reported [163].

Dust loading can also impact the fraction of particles that are resuspended. Dust loading on typical flooring has been observed to range from <1 g/m^2 to over 20 g/m^2 based on sampled dust loads [164]. The change in resuspension fraction as a function of the amount of dust loading suggests that the architecture of deposits affects resuspension. At low loadings, the deposit is expected to be a sparse monolayer, in which particles are thinly deposited along a surface and are not in significant contact with one another. High loadings are likely multilayer particle deposits, in which particles are deposited on top of one another and there is particle-to-particle adhesion and interaction. There are fundamental differences in the resuspension process between monolayer and multilayer deposits, with greater resuspension observed from multilayer deposits [165,166].

Ultimately, carpets are a complex reservoir system that act as both a source and a sink for dust in the indoor environment. Deposition rates of particles into carpet are higher than solid floors (the “sink” effect) [167]. Airborne particles are deposited and stored in carpets, altering the balance and type of pollutants (including particle-bound SVOCs) present in the carpet over periods of years to decades [168]. Some industry reports emphasize the sink aspect of carpets, suggesting that carpets can reduce particle concentration in the air [169]. However, resuspension (the “source” effect) is also higher. Most studies have found that the fraction of settled dust that is resuspended during a resuspension event is higher for carpets than for hard flooring. Because of this storage and increased resuspension fraction, these combined factors generally result in higher particle concentrations in the air compared to hard flooring, especially under occupied conditions [5,155,167,170]. Thus, carpets are an important reservoir of indoor contaminants for exposure [6].

2.6.2. Resuspension is influenced by particle size, humidity, and carpet properties

Particle resuspension is strongly size dependent, and the difference in resuspension fractions among floorings are more pronounced for coarse particles than for fine particles. For example, for the size range of 0.4–10 μm, statistically significant differences based on carpet versus hard flooring were observed for particles >3 μm in diameter [161]. Tian et al. (2014), found no statistically significant differences between the resuspension fractions for carpet and hard flooring for particles sizes between 0.4 and 3 μm in diameter. In addition, multiple studies have demonstrated that within the particle size range of 0.4–10 μm, resuspension fractions and resuspension rates increase with particle size, consistent with theoretical predictions of size-resolved particle detachment [152].

Important resuspension factors include surface roughness and RH. Surfaces with micro-roughness smaller than the particle diameter decreases the contact area and associated adhesive forces between the particle and surface [171]. Humidity effects are complicated and depend on the composition of both the flooring and particles. For example, Salimifard et al. (2017) [172] found that the resuspension of hydrophilic biological particles decreased with increased RH, but RH did not affect the resuspension of hydrophobic particles.

Carpet type and condition likely influence resuspension. The resuspension fraction from high-density level loop carpet was found to be intermediate between that of cut pile carpet and hard flooring [161], indicating that resuspension rates can be manipulated by carpet choice. Also, the surface chemistry of old/worn and new carpet can be quite different. The organic films built up on the carpet fiber over time might alter the surface chemistry, and therefore impact adhesion and resuspension. Rosati et al. (2008), reported that new carpet was associated with higher emission factors compared to older, worn carpet [173]. This was likely due to the fact that at higher RH conditions new carpets release more particles due to the dampening of static electricity, while older carpets become “sticky” at high RH and trap in particles. It may have also been attributed to difference in dust loading, surface chemistry and carpet fiber condition. These results suggest that the carpet condition, construction, nature of organic films and moisture should be taken into consideration in the discussion of resuspension.

2.6.3. *Exposure and exposure assessment from carpet dust*

Microbial and chemical exposures may occur via different exposure routes such as inhalation, ingestion, and dermal contact [174]. Inhalation is likely the most common exposure route of microbes in house dust among adults, while inhalation, ingestion, and dermal contact are common among infants and children, due to hand-to-mouth and crawling behavior. Skin contact may be especially important in considering asthma development [175]. However, the health risks posed by these different exposure routes need to be better assessed. For microbes, some limited evidence in an animal study suggests that exposure via different routes may be additive [176].

Carpets serve as a reservoir for dust containing some key exposures, especially inhalant allergens [138]. The prevalence of allergic diseases has increased during the 20th century, with hay fever increasing earlier in the century and asthma increasing in the latter half of the century [177]. Asthma development and disease exacerbations can be caused by domestic environmental exposures [178]. In the 1980s, the confluence of the building of warmer and tighter homes and more carpets in the United Kingdom, New Zealand and Australia, where asthma has become common, led to the hypothesis that exposure to dust mites and their excreta could be one of the causes of the asthma epidemic in these communities [177]. Most notably, not only do carpets serve as a reservoir for dust mite allergens, but dust mites can live in carpets. Interventions to reduce asthma through dust mite reduction, including acaricide use in carpets, date back more than 30 years [179], yet to our knowledge, no studies have solely targeted carpets. Still, it is well established that carpets can serve as reservoirs for allergens that cause asthma exacerbations, including those from dust mites, cockroaches, mice and furry pets [6]. Homes with carpets have also been found to have higher levels of other chemicals that have been associated with asthma, including the phthalate DEHP, which was associated with asthma symptoms in a study in Sweden [180,181]. While it is clear that carpets can serve as reservoirs for exposures relevant to asthma [6], ongoing research is still investigating links between carpets and asthma, including a recent large study of children living in 7 cities in China where having a carpet in the home was one of the stronger risk factors identified with current asthma [182].

Exposure assessment in the indoor environment is complicated by a variety of factors, but research indicates that measuring dust from carpets and floors can be a better surrogate for long-term exposure than short-term air samples. Short-term air sampling and collecting vacuumed floor dust often yield different exposure assessment, likely because microbial communities in the air change rapidly with time and particle size distributions of the dust will vary [152,183,184]. For instance, in a study conducted in 176 homes in the Midwest region of the United States, endotoxin and β-glucan were sampled by using inhalable and PM_1 (particulate matter smaller than 1 μm) aerosol samplers for 24 h and by vacuuming floor dust. Correlations between the three sample collection methods were poor: the correlation in endotoxin concentration varied from 0.26 to 0.34 and for β-glucan concentration from 0.04 to 0.18 [106]. In another study, 5-day air samples were compared with vacuum samples from floor and bed after analyzing the samples by ITS amplicon sequencing. The taxa in air samples clustered separately from bed and floor, whereas the two vacuumed samples had some overlap in taxa [185]. In one study, specific fungal taxa were well correlated between settled dust and indoor air, although the relationship was weaker for all fungi [186]. In another study, all the dust collection methods (settled and vacuumed dust) correlated with each other and did not have significant differences in concentrations or detected fungal species [187]. The ten most common fungal species were the same in all the dust sample types as well in inhalable air samples, collected for 48 h indoors. However, the proportions of the different taxa in indoor air samples were more similar to the simultaneously collected outdoor air samples. The results indicate that in addition to being a reservoir for dust resuspension, vacuumed floor dust can reflect long-term exposure and is less affected by the changes in the outdoor air concentrations.

2.6.4. *Fungal growth in dust and implications for exposure*

Microbial growth under elevated RH conditions in carpet has the potential to substantially impact human exposure through resuspension [113]. Resuspension of dust from the floor can contribute to about 83% of airborne bacteria and 66% of airborne fungi [188]. There is some limited toxicological data on the consequences of long-term respiratory exposures to fungi. An improved rodent model of nose-only exposure [189] has shown that common indoor fungi elicit varying pulmonary immune responses and target tissues include the larynx, lung, and bronchial lymph nodes. Mice repeatedly exposed to *Aspergillus fumigatus* resulted in allergic inflammation that was dependent on the viability of fungal conidia [189–192] whereas repeated subchronic exposure to *Stachybotrys chartarum* resulted in a mixed T-cell response that was dependent on the production of submicronic fragments [193]. The varying pulmonary immune responses are elicited based on the viability, metabolic activation, and type of particle inhaled. Interestingly, histological examination of lung tissue derived from mice exposed to fungal test articles revealed, for the first time, a continuum of pulmonary arteriole hyperplasia that could result in modulating downstream cardiac endpoints and is the subject of continued research. Utilization of rodent models of repeated fungal exposure may provide further insight into the pulmonary immunological responses to various fungi identified in molecular analyses that may be aerosolized following abiotic or biotic disturbance to carpet dust reservoirs.

The traditional paradigm of indoor fungal exposure has considered the inhalation of fungal propagules such as spores and conidia, but, as noted above, cellular fragments can also impact health. Fragmentation of fungal spores, chlamydospores, yeasts, and hyphae can also result from abiotic and biotic processes including fungal autolysis, mechanical severing of spore/hyphae cross walls or septa, grazing of fungi by other microorganisms, protozoans and micro arthropods as well as mechanical and vibration stresses [100,194]. These fragments of fungi have been termed non-gonomorphic particles due to the lack of morphologically discernible features [194]. *In vitro* chamber studies have shown that fungi frequently detected in indoor environments and carpet are capable of producing non-gonomorphic particles [195–198] and in some cases of abiotic or biotic disturbance, the concentration of these particles can be greater than spores [199]. The clinical relevance of non-gonomorphic particles has also been described in the peer reviewed literature and shown to be immunostimulatory as the particles contain cell wall components such as (1 → 3)-β-D-glucan [200], high molecular weight antigens [196], mycotoxins [201], and allergens [201,202].

2.7. Q7: What more should we know about this resuspension of dust and implications for exposure to carpet?

A number of experimental and modeling studies have been conducted to characterize human-associated particle resuspension from indoor surfaces. Despite this, many fundamental research questions remain on identifying the important factors that influence dust resuspension from carpets, how to improve resuspension models, and understanding associated inhalation exposures.

2.7.1. How particles and carpet influence resuspension

We need to better understand how the biological and chemical content of settled dust and resuspended dust vary with particle size. Particle size strongly impacts the adhesion force, resuspension rate/fraction, mass emission rate, inhalation exposure, and deposition in the human respiratory system. Size-dependent processes can influence the redistribution of microorganisms and particle-bound chemical contaminants within an indoor space. Little is known with regard to the factors that affect changes in the size distribution of carpet dust over time, such as deposition, agglomeration, dissolution, hygroscopic growth at elevated RH, and partitioning of SVOCs. Additionally, we need to consider the sources of indoor particles because different sources will contain varying microbial communities. We also need to learn how particle adhesion and resuspension vary among the vast diversity of microorganisms found in carpet dust. There exists very limited empirical data on adhesion forces and resuspension fractions for bacteria and fungi in contact with different types of carpets [152]. Intrinsic properties of bacteria and fungi are expected to influence their adhesive interactions with carpet fibers. Such properties include: bulk geometry and aerodynamic diameter; shape (e.g. cocci bacteria, elongated fungal spores); surface morphological features (such as pili along bacterial cell surfaces); the nano-scale surface roughness of the microorganism; and surface hydrophobicity, which can be species dependent [203–205].

We also do not yet understand how resuspension and exposure are impacted by variability among carpets of different fiber types, backing types, and construction differences (cut pile vs. loop, stitch rate, density, denier [fiber thickness], etc.). A better understanding of the differences in resuspension between carpet types and between different carpet types and hard surfaces for the same dust loading would be helpful in directing improved future design and for making recommendations for different indoor settings. However, quality assurance in these studies is of utmost importance. For instance, a pair of industry-funded resuspension studies that were not peer-reviewed did not include a statistical analysis or quality assurance measures of particle seeding/loading, particle embedment, or reproducibility of resuspension. The high variability in the results and lack of statistical comparison precludes making a definitive statement about the flooring effect for the samples tested or generalizing the findings from these studies [206,207].

It is also unclear how electrostatic effects influence particle adhesion and resuspension from carpets under variable RH. Electrostatics and moisture are two factors that are dynamically related to one another. The relative importance of capillary and electrostatic adhesion forces varies with RH [204]. Both forces can be influenced by the hydrophobicity and wettability of the particles and carpet fiber, the charge carried by the particle and carpet fiber, and contact electrification due to the repeated contact and separation of feet with the carpet. If the particle and carpet fiber carry charge of the same polarity, the particle may experience an electrostatic repulsive force from the carpet, thereby making the particle easier to detach. Future research is needed to better characterize the impact of electrostatic effects on the resuspension of biological and abiotic particles from carpets.

2.7.2. Improved modeling of resuspension

We need further research on how to model particle resuspension from carpet fibers. Current models perform reasonably well for evaluating resuspension from hard flooring due to human walking, but these models do not directly apply to carpets. Research into the complex airflow patterns across and within porous carpet fiber media during footfalls must accompany these modeling efforts. Specifically, new experimental data on the friction velocity across the carpet fiber surface is needed to model aerodynamic lift and drag forces induced by different types of human-carpet contacts, such as infant crawling and adult walking. These models also need to consider the structure of dust deposits within carpets [173] and how the structure affects size-resolved resuspension fractions/rates and particle adhesion forces.

It is also unclear how to link known resuspension mechanisms and models for individual particles to estimate resuspended particle size distributions in both the breathing zone of occupants and bulk air of the room. Also, in order to accurately estimate human exposure to resuspended dust from carpets, new research is needed to characterize the transport and dispersion of resuspended particles around the human body during different forms of locomotion, such as between crawling and walking [153]. Such research can be aided by computational fluid dynamics (CFD) simulations with Lagrangian particle tracking [208].

2.7.3. Research on the implications of resuspension for human exposure

We need to better understand the contribution of carpet dust resuspension to daily-integrated inhalation exposures. It has yet to be determined what fraction of PM_{10} mass inhaled throughout the day can be directly attributed to floor dust resuspension.

Finally, another important question is how the use of walk-off mats at the entrance of buildings affects particulate matter exposure. Generally, walk-off mats are used for aesthetic purposes to avoid visible soiling of other flooring materials, but there are some preliminary data that indicate that the enhanced deposition of carpet used in the entryway could help prevent contaminants from entering the remainder of the building [209]. Open questions include requirements for the length or material to effectively reduce contamination of the indoor environment. Shoe removal at the entrance of a home may also reduce the amount of soil and other materials tracked inside [126,210,211].

2.8. Q8: What standards, guidelines etc. currently exist for use of carpets in US buildings?

Consensus standards are generally lacking on the recommended use of carpet indoors. The National Center for Healthy Housing, a national nonprofit organization in the US, produced a document in 2008 outlining facts about carpets and healthy homes [212]. Their recommendations included: 1) avoid wall to wall carpet in rooms where individuals with asthma or allergies may be present; 2) avoid carpeting rooms that may be exposed to moisture; 3) air out the carpet before installation to limit exposure to VOCs; and 4) use a vacuum that has a High Efficiency Particulate Air (HEPA) filter and use it weekly or every other week [212]. The Institute of Medicine, in their 2000 report entitled Clearing the Air, also recognizes carpet as a major reservoir for allergens [133]. A report compiled for the U.S. Environmental Protection Agency also recommends not installing wall-to-wall carpet close to toilets and bathing fixtures such as tubs and showers [213].

Carpet manufacturers and cleaners have also created voluntary standards. The Carpet and Rug Institute, the trade association for the North American carpet industry, developed the Green Label certification program in 1992, in which they tested and labeled carpets to let consumers know which ones meet low emissions criteria [214]. This program ended in 2009 and was replaced by the Green Label Plus™ (GLP) which includes testing requirements as outlined by the California Department of Public Health (California Section 01350 (version 1.1, followed by version 1.2 in 2017) [215]. To meet Green Label Plus™ Certification, the emission factors for various VOCs must be less than specified rates. For instance, formaldehyde emissions must be ≤ 17 μg m^{-2} h^{-1} [216].

For cleaning, the Institute of Inspection Cleaning and Restoration Certification (IICRC) is a trade association of the cleaning industry.

Their ANSI/IICRC S100 is a standard for professional cleaning of textile floor coverings [217].

Indoor environmental quality standards are continuing to be developed and recognized for their importance. This is illustrated by ASHRAE Standard 62 on ventilation. This standard has addressed indoor air quality in all revisions since 1989 but was expanded in the 2019 revision, which greatly increases the level of detail on indoor environmental quality and, for the first time, considered a verification that the indoor air quality met the design intents. Standards related to sustainability concerns also exist and are described in Question 10.

2.9. Q9: What might we consider when developing future standards/guidelines/best practices etc.?

Science-based policy, laws, and regulations are an integral aspect of improving and maintaining public health. These policies are based on evidence that helps to inform the balance between risks and benefits. Typically, we do not have a comprehensive understanding of risks and benefits of building materials prior to their introduction into commerce, construction, and housing rehabilitation. Both public health and housing affordability are important aspects of making recommendations for housing [218–220]. In some cases, additional knowledge of risks and benefits changed existing recommendations for building material use. For example, lead-based paint was permitted for decades as a material that promoted durability, a superior hiding and drying agent, and even improved sanitation. Additionally, formaldehyde was permitted in insulation and flooring as an agent that promoted greater durability and adhesion. These and other substances were studied and in some cases banned after the health risks were understood to outweigh any social and economic benefit [221,222].

Carpets are one aspect of an integrated building system that should be managed to encourage occupant health and safety. Therefore, new standards, guidance and best practices for carpet installation and maintenance should account for the variability of environments in which carpets exist and the multicomponent structure of carpet consisting of the top layer of fiber, backing materials, and adhesives. Each component will have its own contribution to the chemistry and microbiology of the carpet system. Environments can include different building types, such as residential, school or office. Moisture management is a fundamental part of all building design, construction, and operations, and may be particularly relevant for areas of carpet flooring.

Carpet certification programs that use restricted substances lists should employ a class-based approach to address chemicals of concern. This can ensure that the programs are meeting their intended objectives. For instance, multiple existing standards restrict the presence of long chain perfluorinated chemicals, perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), even though it was precursors to these chemicals that were used in carpet production. Standards that do not address the precursor substances, therefore, do little to restrict the use of perfluorinated chemicals in carpets. One solution to this problem is to restrict the broader class of PFAS. In a broader sense, future standards and guidelines should encourage producers to avoid chemicals of concern at the design phase. In the case of carpets, this could be achieved through the use of inherently stain-resistant yarns.

Future evidence-based guidelines for flooring require that we understand the risks and benefits of using carpet under a variety of circumstances. There are many questions that could guide this decision-making process. Do the benefits of carpet (such as cushioning/prevention of falls, comfort, aesthetics) outweigh the risks (such as exposure to chemicals and biological agents, resuspension of particles)? The answer to this question may differ depending on any given set of circumstances and the risks/benefits of alternative flooring materials. How do other housing systems, such as ventilation, moisture and pest control, and typical cleaning practices, interact with carpeted surfaces? What are the financial and health implications of increased use of carpets of varying types on building maintenance, capital improvements, and overall sustainability? Most importantly, how will improved knowledge affect both consumer behavior and corporate marketing strategies? Ultimately, an improved understanding of the risks and benefits of different flooring materials will allow us to improve health, housing sustainability, and overall societal and economic benefit.

2.10. Q10: What types of sustainability practices are or may be implemented to reduce environmental impacts of the use of carpet in buildings?

Sustainability encompasses economic, social and environmental concerns [223]. In the United States, over 4 billion pounds of carpet enter the solid water stream each year [224] with only 5% of carpet recycled in 2016 [225]. Enhancements to carpet sustainability practices could help to reduce the environmental impact of this material. Sustainability of carpet should include consideration of proper maintenance, such as vacuuming and use of cleaning agents, as well as disposal and replacement of the carpet due to normal wear or from damage by flood waters or smoke exposure. The broad nature of carpet types, building types and human sensitivity will require collaboration of government, industry and academia to formulate new standards, guidance and best practices for carpets that best integrate them into building system while allowing for proper maintenance and sustainability.

2.10.1. Sustainability in industry

Carpets can have implications not only to human health, but to the environment as a whole. One study found that the production of one 0.09 m^2 section of wool carpet requires 20.42 MJ of energy creating 6.35 kg CO_2-equivalents of emissions, while a nylon carpet uses 25.42 MJ of energy and produces 4.80 kg CO_2-e of emissions [10]. As such, all industries, including carpet manufacturers, are embracing sustainability-oriented innovation (SOI) as a way to achieve a long-term competitive advantage in the marketplace [226,227]. The discovery that environmental conservatism, resource efficiency, and organizational identity could be tied together to profitability has led companies to adopt green business models [223,228].

The business model of Interface Inc, a global market leader in the modular carpet tile business, has been used in case studies on sustainability. This is to demonstrate that a firm which produced, per year, 10 tons of solid waste, 605 million gallons of contaminated water, 704 tons of toxic gases, and 62,800 tons of $CO_{2,}$ could be radically changed with a "Mission Zero" strategy and still maintain market profitability [229]. This multi-year effort entailed revised processes, new nylon formulations for ease in recycling, new material sourcing based on recycling of spent industrial fishing nets, an anaerobic digestion process from food waste to produce natural gas, and lease and recycling efforts [230–232]. Challenges remain in carpet recycling efforts [233].

Industry-, NGO-, and government-driven research, guidelines and standards related to indoor exposures and disposal of post-consumer waste can become a part of sustainability initiatives for carpet. This might include consideration of proper maintenance and cleaning (e.g., wet and dry vacuuming), as well as appropriate cleaning agents for existing materials, and development of advanced materials which preclude the use of surface treatments, limit microbial growth under humid conditions, and avoid the introduction of chemicals with unintended adverse consequences.

2.10.2. Recycling

As carpet is made up of many different materials, some may be recovered, recycled, and used for new carpets or other applications [233,234]. Many manufacturers have carpet recycling programs. Carpet America Recovery Effort (CARE) is an organization that promotes and advances carpet recycling efforts [235,236].

The movement of carpet material through a recycling system is a labor-intensive process and usually requires activities be carried out manually [237]. Fibers can be reprocessed from carpet waste, but once the fiber is removed from the backing, the remaining carpet waste is usually sent to a landfill [233]. Carpet disposed of in an incinerator may emit emissions such as per- and polyfluoroalkyl substances from stain-resistant coatings, though one study found only trace levels of PFCs from emissions due to the combustion of carpet [238].

Plastics can also be reprocessed separately from fibers and used for more carpets or molded to new plastics, though the resulting engineered plastics have poor mechanical properties [233]. Different polymers and fillers recycled from carpet have also been tested as feedstock materials for inclusion within structural composites for load-bearing applications, such as concrete [233,234]. Sustainable recycling of carpet will require screening and product design that prevents the reintroduction of harmful chemicals into the marketplace. Carpet design should eliminate these compounds that inhibit recycling efforts, such as phthalates [239]. In addition, the potential presence of PFAS, either in the carpet itself or subsequently applied to the carpet as a stain resistant coating, may affect the ability to recycle a given carpet [238].

2.10.3. Sustainable carpet materials

Wool carpet fiber is biodegradable, although the carpet backing may not be [240]. A biodegradable carpet backing made of lignin-based adhesive was created to replace the normal latex backings [241]. Using wool carpet with the lignin-based backing in the future could allow the carpet to be completely biodegradable and limit waste. Multiple carpet manufacturers have also created carpet utilized from recycled materials. For example, Mohawk Industries and Shaw Floors have each created carpets made of polyethylene terephthalate (PET) taken from recycled plastic bottles [242,243]. Several companies have also created a recycled carpet backing. Tarkett created a carpet tile backing, DESSO EcoBase, made of at least 75% recycled content which can be removed from the carpet and recycled at the end of its lifetime [244].

2.10.4. Sustainability standards

In the first decade of this century, rating systems for sustainable buildings included an Indoor Air Quality (IAQ) component but were mostly known only to designers and owners of commercial buildings. In the past decade, multiple programs that address the impacts of IAQ have been created to provide information about products, their contents and components. Manufacturers and retailers are more often expected to provide such information to consumers. Some programs list forbidden materials, while other programs also estimate exposure under specified conditions. Transparency is increasingly becoming an expected feature of products used in the indoor environment.

Heightened interest in green buildings and indoor environmental quality have led to the creation of several carpet sustainability standards that go beyond the VOC emissions requirement of CRI's Green Label Plus™ program [214]. Products that comply with these standards tend to be more expensive.

- *NSF/ANSI 140 - 2015: Sustainability Assessment for Carpet.* This commercial carpet standard was developed by a multi-stakeholder process and is employed by government agencies interested in environmentally preferable procurement. It incorporates the VOC emissions requirements of Green Label Plus™, requires ingredient disclosure down to 1%, prohibits persistent, bioaccumulative, and toxic (PBT) substances greater than 0.1% as well as long-chain PFAS, and provides additional credits for further minimizing total VOCs, carcinogenic VOCs, formaldehyde, and PBTs. The standard does not address carpet adhesives or padding [245,246].
- *Cradle-to-Cradle Certified (C2C).* C2C is a product certification standard that addresses multiple attributes of sustainability, including "Material Health." Products that obtain the C2C Silver level must not contain greater than 1000 ppm of substances on the certifier's restricted substances list, which includes heavy metals, flame retardants, phthalates, two long-chain PFAS and other chemicals of concern. Carcinogens, mutagens, and reproductive toxicants are also prohibited above 100 ppm [247].
- *Oeko-Tex 100.* The Oeko-Tex 100 standard bans or restricts certain chemicals in textiles, including carpet fibers. The list of restricted substances includes heavy metals, flame retardants, phthalates, certain long-chain PFAS and numerous other chemicals of concern [248].
- *Living Building Challenge.* LBC is a green building certification standard that requires products used in construction of a building to avoid certain chemicals. Like C2C and Oeko-Tex 100, LBC's restricted substances list includes heavy metals and a number of SVOCs [249].

3. Discussion

Carpet type, installation, and manufacturing has changed over the years, largely in response to consumer demands. Some chemicals have been removed from the manufacturing process through various programs (ex: Green Label Plus™), installation is moving towards modular products rather than large rolls, and the preferred fiber has changed from nylon to polyester carpet due to style preferences and cost. Sustainability concerns have led to efforts to promote carpet recycling and more sustainable carpet materials. However, manufacturers have not seen a large interest from residential consumers to create recyclable carpet products, and consumer education may be required on this issue.

Carpet maintenance should continue to be an important consideration prior to any carpet installation given the impact of carpet dust on human exposure highlighted here. There is a need for proper cleaning practices to be more thoroughly described to consumers on both a residential and commercial level. For example, it would be helpful to specify frequency and duration of carpet vacuuming required in order to meet a specific threshold of dust loading and/or resuspension from walking. These cleaning recommendations may differ widely under various circumstances due to variability including carpet type, traffic patterns, and commercial versus residential spaces. It is especially important to consider maintenance costs for low-income families [250], for whom high-quality vacuum cleaners may not be affordable [251, 252]. Within the professional cleaning industry, proper personal protective equipment needs to be used following exposure guidelines, which is especially important for disaster situations or demolition events.

3.1. The future of carpet

Designing carpets that have the ability to improve indoor environmental quality related to dust retention, resuspension, and microbial growth should be an environmental health goal. This goal also needs to involve consumer education on why these properties of carpet are important to the indoor environment and occupant health. Currently, consumers tend to assess the cleanliness of carpet through visual inspection, which may not be an accurate representation of cleanliness as some carpets are designed to appear clean even when they are not. Consumers need to understand the benefits of improvements in carpets for environmental health to warrant purchasing any products that may be developed. To provide this education, we also need a thorough understanding of how carpets impact indoor microbiology and indoor chemistry.

Future carpet designs could conceivably utilize specific properties to reduce potentially harmful exposures. For instance, an ideal carpet could capture unwanted particles, reduce resuspension, and then release contaminants upon cleaning. Specific target values, such as a certain resuspension rate associated with health outcomes, could help in achieving these goals and could mimic the Green Label Plus™ program. Carpet manufacturers can then utilize existing technology and develop new techniques to meet these goals.

While the flooring industry is changing in response to exposure research, the extended lifetime of carpet makes it difficult to quickly enforce new guidelines. Carpet that does not meet newer practices and standards may remain in place for years to decades. Information must be accessible and understandable to consumers so that informed decisions can be made about sustainability and exposure issues.

4. Conclusion

Carpets are an integral part of our indoor environments. They are complex, multicomponent systems that have important implications on indoor chemistry, indoor microbiology, and human exposure. Eventually, we need to be able to use what we know about carpet to complete a risk/benefit analysis of carpet in a given circumstance, for instance by comparing the risk of increased microbial exposure from carpets versus the reduction of the risk of injury from falls. This risk/benefit analysis could also indicate situations where a carpet should be removed or cleaned. This analysis could potentially change with future development of carpets that promote environmental health by reducing resuspension and therefore occupant exposure. Ultimately, this information can lead to better carpet design and improved recommendations for flooring selection in the indoor environment to improve human health.

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The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government and shall not be used for advertising or product endorsement purposes.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Troy Virgo is an employee of and has financial interests in Shaw Industries, which manufactures carpet. David Wilkinson is an employee of and has financial interests in Tarkett, which manufactures carpet. John Downey is associated with the Cleaning Industry Research Institute, which is a 501c3 nonprofit research institute and professional technical institute. All other authors declare no competing interests.

Acknowledgements

Both the workshop and the development of this manuscript were supported by the Alfred P. Sloan Foundation, grant G-2018-11240. The authors would also like to thank Ginger Chew (Centers for Disease Control and Prevention) for reviewing the manuscript. We also would like to thank workshop participants Joe Hughes (IAQ Training Institute), Jim Williams (Mohawk Industries), Julie Brumbelow (Shaw Industries), Paul Tucker (Carpet and Rug Institute), Heather Allen (The Ohio State University), and Jordan Clark (The Ohio State University) for sharing their perspectives.

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