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10 Questions

Ten questions concerning green buildings and indoor air quality

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ABSTRACT

This paper investigates the concern that green buildings may promote energy efficiency and other aspects of sustainability, but not necessarily the health and well-being of occupants through better indoor air quality (IAQ). We ask ten questions to explore IAQ challenges for green buildings as well as opportunities to improve IAQ within green buildings and their programs. Our focus is on IAQ, while recognizing that many factors influence human health and the healthfulness of a building. We begin with an overview of green buildings, IAQ, and whether and how green building certifications address IAQ. Next, we examine evidence on whether green buildings have better IAQ than comparable conventional buildings. Then, we identify so-called green practices and green products that can have unintended and unfavorable effects on IAQ. Looking ahead, we offer both immediate and longer-term actions, and a set of research questions, that can help green buildings to more effectively promote IAQ. This article supports a growing recognition of the importance of IAQ in green buildings, and the opportunities for improvements. As the World Green Building Council [95] and others have emphasized, people are the most valuable asset of organizations, and efforts to improve IAQ can improve health, well-being, productivity, and profitability.

1. Ten questions

1.1. What are green buildings?

In general, "green buildings" are structures designed to promote efficient use of resources (e.g., energy, water, and materials) and sustainability (e.g. [93], and to reduce the adverse effects of buildings on the environment). A commonly cited definition of green building is provided by the US Environmental Protection Agency [28]: "Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction."

In recent years, and more specifically, green buildings are typically defined and categorized by green building certification programs. Many countries around the world have their own programs. Early certification schemes include the Building Research Establishment Environmental Assessment Methodology (BREEAM) in the United Kingdom in 1990 [13], and Leadership in Energy and Environmental Design (LEED) in the United States in 1994 [83]. Other major programs include the Deutsche Gesellschaft für nachhaltiges Bauen (DGNB) system in Germany [26], Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan [18], and the Green Star system in Australia [38] [47].

As of October 2016, over 145,000 green certification projects have been completed around the world, using these and other certification schemes [38]. Globally, the percentage of firms with over 60% of their projects certified green is forecast to grow from 18% in 2016 to 37% by 2018, with a greater proportion from developing markets [89].

Today, more than 31 green building certification programs and 55 schemes within those programs (e.g., for different types of buildings) are used in over 30 countries around the world, and some programs (such as BREEAM and LEED) are used in multiple countries [86]. Other programs have emerged with goals to promote indoor air quality and occupant health, such as the WELL

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building standard [87], even if not termed green building. However, it is unclear whether such programs are any more effective than green building programs in promoting healthy IAQ. Despite the prevalence of green building certification programs and several common features, no internationally consistent criteria exist for green buildings. Also, relatively little systematic research has been conducted to determine whether and how elements of green building programs improve IAQ (e.g., [62,79].

In conclusion, green buildings are implemented by various programs and criteria around the world. They typically emphasize efficient use of energy and resources and, to lesser extent, healthy indoor air quality.

1.2. What is indoor air quality?

Similar to green buildings, "indoor air quality" has no universal or standard definition. In general, IAQ is related to pollutants (e.g., biological, chemical, and physical) within indoor environments that can affect the health of occupants. IAQ is considered a subset of indoor environmental quality (IEQ); the latter includes factors such as lighting, ergonomics, acoustics, and temperature in addition to pollutants.

Indoor air quality definitions can vary depending on perspectives of the human user, the indoor air of the space, and the sources contributing to the indoor air pollution [12]. A definition provided by the US Environmental Protection Agency [28] is as follows: "Indoor Air Quality (IAQ) refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants."

However, in the US as in many other countries, no federal law specifically regulates IAQ [77], even though people typically spend more than 90% of their time indoors, pollutant levels are typically several times to several hundred times higher indoors than outdoors, and consequently indoor air typically accounts for over 90% of human exposure to pollutants [64]. Some agencies do offer guidelines, such as World Health Organization [90], for the protection of public health from common chemicals in indoor air. For example, the [90] indoor air quality guideline for formaldehyde (30-min average concentration) is 100 μg/m3 (0.08 ppm).

While air quality regulations in the US [29], European Union [30], Australia [9] and other countries regulate "ambient air," the term has been interpreted as "outdoor air," or air external to buildings, excluding indoor air. While outdoor air quality can affect the indoors, and indoor air contains pollutants from both outdoor and indoor origin, indoor air quality is concerned with the air within buildings and other indoor spaces, regardless of the sources of pollutants.

Indoor air quality is difficult to measure and assess for many reasons; among them: (1) The lack of consistent metrics, standards, and consensus on what constitutes favorable IAQ; (2) The diversity and complexity of pollutants found indoors that can affect human health and well-being, even at exceptionally low levels; (3) The inadequate understanding of links between pollutant levels indoors, exposures to those pollutants (both individually and in mixtures), and their effects (both acute and chronic); (4) The range of health effects related to indoor pollutant exposures, and that the same pollutant exposure can affect different humans in different ways; (5) The question of whether the pollutants being measured are the ones that really matter; and (6) The lack of requirements to measure and monitor IAQ, leading to a lack of awareness of potential problems and remedies.

In conclusion, attention to IAQ is often voluntary from a regulatory perspective, though important from a health and well-being perspective. While some agencies offer guidance, no consistent metrics or regulations exist for determining and assuring the health of indoor air environments.

1.3. Do green building certification schemes address IAQ?

Since the birth of green building certification schemes, IAQ has been included as one of their default elements. Currently, IAQ is included, in some way, in all schemes presently in use. However, we lack systematic information on how many of the credits addressing IAQ are actually exploited during the certification process and, if all are awarded, whether this would significantly improve IAQ.

The categories that include IAQ in various schemes are differently termed. For example, in BREEAM, IAQ is included in the category for health and well-being, in LEED and Green Star in the category called indoor environmental quality, while in DGNB in the category describing socio-cultural and functional quality. In addition to credits for IAQ, categories that include IAQ also provide credits for other aspects related to IEQ, such as for daylight, artificial light, acoustic and thermal environment.

The contribution of credits for IAQ in green building schemes is on average 7.5%, and spans from about 3% to 11%, based on a recent evaluation of 55 green building schemes in 30 countries [86]. The relatively small percentage of credits for IAQ may be considered as inadequate incentive to pursue these credits, or even as inadequate representation of the importance of IAQ. On the other hand, green certification schemes include many components, and any single component (with the exception of perhaps energy performance) may not receive a large percentage of credit.

It is useful to examine how IAQ is addressed in the certification schemes and which aspects are awarded. Credits are received for measures related to source control (mainly attained through selection of low emitting building materials and products, but also by use of green cleaning products and policies, and low emitting equipment), for ventilation (mainly by specifying minimum ventilation requirements or referring to relevant standards or codes prescribing ventilation, and also specifying requirements such as minimum filtration levels, location of main air intakes, and main exhaust outlets), and for conducting indoor air quality measurements (either before or during occupancy, or during both periods). Among the 55 certification schemes reviewed by Ref. [86]; 100% of them award credits for ventilation, 77% award credits for source control and 66% for conducting IAQ measurements.

Credits are also received if levels of specific pollutants are targeted. The most frequently addressed pollutants are volatile organic compounds (VOCs), formaldehyde, and carbon dioxide (CO_2). These three pollutants are included in at least 65% of the schemes reviewed by Ref. [86]. In addition, requirements are defined for levels of asbestos, microbes, ETS, carbon monoxide (CO), total VOCs (TVOC), sulphur oxides (SO_x), nitrogen oxides (NO_x), radon, particles, ammonia, ozone and semi-volatile organic compounds (SVOCs) but the requirements for these pollutants are present less frequently in the schemes than for the three pollutants mentioned above, and none are mandatory.

In addition to direct credits for IAQ, credits in other categories can indirectly affect IAQ. For example, site selection can influence outdoor air quality. Thus, the building envelope quality and tightness, as well as type of ventilation, can affect the migration of pollutants between indoors and outdoors, and energy-efficient systems can improve or impair IAQ depending on outdoor air quality. Credits for these criteria generally do not add to the total credit for measures for promoting IAQ.

Many certification schemes allow "trading" of credits across different categories and, with few exceptions (e.g., DGNB), it is the total number of credits awarded that determines the level of building certification, not the credits received in each category. Consequently, in some schemes, the highest certification level can be achieved without receiving any credits for IAQ.

To manage this issue and promote IAQ, some schemes introduced mandatory requirements for addressing IAQ. For example, in the 2009 version of LEED, buildings awarded certification had to meet the requirements of ASHRAE 62.1 ventilation standard [6] and apply the environmental tobacco smoke (ETS) control. In DGNB, each category needs to receive a minimum number of credits; otherwise, the building cannot be awarded certification. Although seemingly effective in promoting credits from all categories, DGNB does not mandate which criteria should be addressed within each category. This approach, as a result, may not sufficiently promote IAQ if credits for other IEQ criteria would suffice and be easier to receive. Mandating criteria addressing IAQ is further tackled in the Green Mark Pilot 2015 proposed by Building Construction Authority in Singapore [10]. They defined prerequisite requirements for all categories for a building to be awarded certification. In the case of IAQ, these prerequisites include airtightness and leakage, minimum ventilation rate, filtration media and time of pollution, and the use of low volatile organic compound (VOC) paints.

In conclusion, credits for IAQ are included in the certification schemes, and some schemes include minimum requirements for IAQ. It can be argued whether current credits are sufficient and effective to promote better IAQ in green buildings. Certification schemes mainly require ventilation as the major measure to control IAQ and less so the source control. A building can receive the highest level of certification, in many schemes, without any credits for IAQ. Consequently, the fact that criteria addressing IAQ are included in the certification schemes does not guarantee that they are addressed during the certification process.

1.4. Do green buildings have better IAQ than conventional buildings?

At least three scores of studies have documented indoor environmental quality in the cross-section of green buildings certified with different schemes, mainly LEED, Green Star and BREEAM [23]. Some studies compared IEQ in green buildings with matched or unmatched regular (conventional) buildings that were not certified by any green building scheme. IAQ was examined in about half of these studies [3,23].

IAQ in green buildings was mainly assessed using post-occupancy surveys, which typically were not the same in various studies. These surveys collected information on IAQ as perceived by the occupants. Only in a few studies, the actual measurements of IAQ were carried out by documenting the levels of CO_2 or other pollutants, and measuring the ventilation rates, so the actual exposures and their levels in the buildings could be described (e.g., [57,62].

In general, the studies indicated that the occupants of green buildings rated IAQ to be high or that they were more satisfied with IAQ than the occupants in conventional buildings (e.g., [1,2,15,21,41–43,54–57,62,79]. In a few cases, the opposite result was seen; that is, the ratings of IAQ were lower in green buildings compared with conventional buildings [16,53,80]. In some studies, there was no observed effect of green certification on the ratings of IAQ as reported by the occupants of green buildings (e.g., [4,52]), or the results of subjective evaluations were equivocal (e.g., [40]).

A few studies suggested that IAQ was improved in green buildings because of lower prevalence of health symptoms as reported by occupants; some of these symptoms can be attributed to exposures to air pollutants (e.g., [14,21,37,57,62]). One study, which compared green and conventional hospitals, showed reductions in mortality rates, blood stream infection rates and medicine consumption in the green hospital; some of these effects could occur because of improved IAQ [81].

A limitation of the studies that examined IAQ in green buildings is that none attempted to explore whether the effects of improved IAQ can be attributed to the higher number of credits awarded for IAQ in green buildings. The studies implicitly assumed that this was the case. Another major limitation is that the main evidence for improvements in IAQ arises from subjective evaluations. In most cases, no measurements were performed in parallel to subjective evaluations to document whether the pollutant levels and exposures in the investigated green buildings were truly different from conventional buildings. It was also not documented whether thermal conditions were different, temperatures and relative humidity being an important modifier of the perception of quality of indoor air [31]; [32].

Perceptions of indoor air quality can also be attributed in part to other factors, not just pollutant levels or actual exposures. For example, it is well documented that the occupants of green buildings are proud of being able to work in their buildings [46], many of which are iconic buildings and owned by successful businesses. The overall high satisfaction of working in these buildings may propagate on satisfaction with IAQ. This postulation is supported by studies that show that occupants of green buildings are apparently more tolerant to less optimal indoor environmental quality [23].

Many studies reporting measurements in green buildings did not adequately control their findings for several potential confounding factors, and did not perform satisfactory statistical analyses of the measurements. Further, in many studies, responses from different cohorts of people working in different buildings were compared. The studies attempting to match the green buildings and the conventional buildings to control for confounding factors are sparse (e.g., [62].

In conclusion, the majority of available measurements in green buildings do show that IAQ, as perceived by building occupants, is improved. The studies do not make sufficient connection, however, between these results and the physical and chemical measurements of actual exposure levels, and between these results and the credits awarded by the certification schemes for managing IAQ.

1.5. How can green practices compromise the IAQ of a green building?

A variety of green practices can be applied in green building projects to achieve a certification level as high as possible [78]. Some of these practices award credits for solutions related with reducing resource use, environmental impacts, or CO_2 emissions, such as maintaining minimum code ventilation requirements, using recycled materials, or promoting low-carbon commuting. However, some green practices can also compromise IAQ in green buildings. Further, the cross-category interaction is not accounted for in certification schemes, whereby positive credits obtained in one category can negatively influence indoor air quality.

One example of green practices having potentially negative consequences for IAQ is the use of waste-based materials, recycled materials, or reused materials. For instance, application of fly ash as an additive to building materials can increase the exposure of building occupants to a suite of heavy metals that may have toxic properties (e.g., [49]. Materials that are recycled or reused can re-emit pollutants that were adsorbed on their surfaces, used in the recycling process, or accumulated in previous applications; potentially toxic materials can also be reused and reapplied in buildings (e.g., [65].

Another example are actions to keep outdoor air supply at minimum rates and reduce the need for cooling and air-conditioning, and supplement them with other less energy demanding solutions. These actions comprise the use of air purification methods and flushing or enhanced ventilation, respectively. The air can be purified with filtration and air cleaning units or equipment that is installed in the system providing ventilation, or as stand-alone solutions displaced in different locations in buildings (e.g., [35,69,70]. The air can also be purified by using building and finishing materials that are especially manufactured to act as the air cleaners (e.g., [22,25,51].

Although it may be expected that air purification systems would benefit IAQ, two major problems have been related with this technology (e.g., [7,70,85,94]. One problem is that the air cleaners may not be as effective as they are claimed to be, or they may selectively remove only some pollutants and be ineffective for the others. The other problem is that some air cleaners during the process of cleaning will generate unwanted products, some even more harmful than the pollutants that are removed. Additionally, some air cleaning and filtration techniques can become the source of pollution if not properly serviced or maintained (e.g., [11,48].

Flushing or enhanced ventilation is usually exercised at night (so-called nighttime ventilation) or during the off-hours when the building is unoccupied. It significantly increases outdoor air supply rates and uses the cooling power of the ambient air to remove the heat accumulated in the building. However, this process can also bring in outdoor pollutants that can accumulate indoors. This is especially problematic in areas with high outdoor pollution and when the filtration and air cleaning systems on buildings cannot adequately remove pollutants from high air volumes. Enhanced ventilation can also break the equilibrium near the surfaces of materials. This can lead to release of pollutants, which are primarily emitted by materials (intrinsic emissions) and also those that adsorb on surfaces and are absorbed in the building structures.

As another common example, outdoor air supply rates may be reduced in order to promote energy efficiency but without compensatory actions such as source control. This can increase concentration of pollutants indoors and reduce IAQ, especially in existing buildings that undergo renovation and retrofit. Tightening of building envelopes can also reduce outdoor air supply rates, which can reduce IAQ, if the volume of air that is infiltrating indoors is not brought back out by the ventilation system or if pollution sources are not concurrently reduced. Tighter structures and reduced infiltration can, on the other hand, reduce the penetration of outdoor pollution indoors, which is important when outdoor levels are undesirably high. Which of the two brings more benefits depends on the particular building and the context.

A frequent feature of green building projects is to locate the building close to urban centers or public transport systems, which can earn credits for location or transport. However, location of buildings close to dense urban areas or major transportation routes may result in poor outdoor air quality that can penetrate indoors, and reduce IAQ. Green solutions for ventilation such as natural ventilation or hybrid (dual-mode) ventilation may result in elevated exposures to outdoor pollution. These solutions may not use filtration and air cleaning technologies to remove pollutants from outdoor air used for ventilation, and thus may impair IAQ especially in cases when outdoor pollution is high.

In conclusion, some green practices may earn credits in green building certifications but result in poor IAQ. These practices include, among others, the use and recycling of products that contain hazardous compounds, energy efficiency strategies that increase indoor pollutants, location of green buildings near urban and transportation emissions, and the use of natural ventilation in areas with elevated outdoor pollution.

1.6. How can green products compromise the IAQ of a green building?

Similar to "green" buildings, the concept of "green" products has no universal or standard definition. Even though some products are marketed as being green, the term does not guarantee healthier products or better IAQ. Recent research has found that products with claims and certifications of green (e.g., green cleaning products, building materials, and furnishings), can nonetheless emit and generate hazardous compounds, and sometimes comparable to their conventional counterparts (e.g., [67,75].

So-called green, natural or organic products or materials can nonetheless contain or generate hazardous constituents. For example, green cleaning products often contain fragrance chemicals (e.g., terpenes) that are primary pollutants, and that react with ozone to generate a range of secondary pollutants such as formaldehyde and ultrafine particles [61]. A comparative analysis of volatile emissions from green and conventional fragranced products, including cleaning products and air fresheners [75], found over 550 VOCs emitted from 37 products, with nearly 25% classified as toxic or hazardous under US federal laws. However, fewer than 3% of emitted ingredients were disclosed on product labels or material safety data sheets. Emissions of carcinogenic hazardous air pollutants from green fragranced products were not significantly different from conventional fragranced products. Fundamentally, if the product contained fragrance, regardless of nomenclature (e.g., green, organic, essential oils, or all-natural) it emitted potentially hazardous air pollutants. Yet nearly all green cleaning product certifications and standards permit the inclusion of fragrances.

As another example, even zero- or low-VOC paints, including ones certified as green, can still emit VOCs similar to regular paints, as well as other problematic chemicals such as SVOCs. In tests of various green certified and conventional paints [67], no significant difference in emissions was found between conventional paints and the low-VOC and zero-VOC paints, and the ultra-low VOC paints showed the highest emission potential. The tested products emitted almost the same spectrum of substances independent of certification marks. Also, some green building materials such as linoleum contain linseed oil, which can release VOCs that react with ozone to generate aldehydes [63]; [45].

In addition to VOCs, green products can also contain and emit a range of other potentially hazardous compounds; these include SVOCs (e.g., phthalates), plasticizers, antimicrobials, and a range of asthma-associated and endocrine disrupting compounds [36,75]. Indoor air quality is heavily influenced by the vast array of compounds emitted and generated from consumer products and building materials, and many types of compounds found indoors today were not present a half-century ago [88].

While numerous organizations and agencies have developed labeling programs for green products, and companies are marketing their products as green, the term is generally unregulated and undefined. Greenwashing, or making misleading or unsubstantiated claims about the environmental benefits of a product, is a well-recognized problem, likely fueled by demand for green buildings and products. Over 500 green certification labels exist in the US alone [24]. A study of nearly 400 green cleaning products in the US and Canada, which collectively made over 1200 green-related claims, found that fewer than 1% of the products made no misleading or unsubstantiated claims [82].

Indeed, green product claims and potential benefits are difficult to verify. Unlike other commodities, building materials and consumer products, even ones called green, are not required to disclose all product ingredients on the label, material safety data sheet, or elsewhere to the public [76]. Also, green product rating guides typically rely on only listed or disclosed ingredients, which can represent just a small percentage of actual ingredients [75].

The presumption that green products translate into good indoor air quality may be precarious. Green products may not promote favorable indoor air quality for a number of reasons, among them:

(1) Green certification standards may allow known hazardous compounds in products, (2) Green products are not required to disclose all ingredients, which can include hazardous air pollutants, (3) Green product claims lack publicly available data for substantiation, (4) Green product guides, which list and sometimes rate green products, typically rely on disclosed information rather than independent product analyses, and (5) Green products used in buildings lack verification and monitoring of their emissions and effects on indoor air quality.

In conclusion, given that consumer products and building materials are a primary contributor to indoor air pollution, truly green products and materials are essential to good IAQ. However, products marketed as green, and related attributes such as natural and organic, often lack scientific substantiation and justifiable criteria for their claims.

1.7. What are implications of climate change for green buildings and IAQ?

Historically, research and attention on the links between climate change and air quality has focused overwhelmingly on the outdoor environment; for instance, the effects of increased temperatures on ground-level ozone. Far less work has examined links between climate and the indoor environment, especially concerning IAQ. However, recent years have seen a growing recognition of the importance of the effects of climate change, as well as extreme weather events on the indoor environment, which translate into considerations for green buildings.

The implications of climate change on IAQ are numerous and complex. Some recent and notable studies (e.g., [34,44,60,71]), have categorized and described these effects. For instance, [60], explored the effects of climate change on factors that govern indoor pollutants: (a) properties of pollutants (e.g., warmer temperatures affecting indoor pollutants from both indoor and outdoor sources), (b) building factors (e.g., reduced ventilation rate and increased air conditioning use), and (c) occupant behavior (e.g., changes in human activities and product use indoors) [34]. examined (a) outdoor environment conditions that increase with climate change (e.g., climate-related events such as heat waves, extreme precipitation, wildfires), (b) influences on indoor environment (e.g., higher temperatures, dampness and mold, particulates and ozone, pollen allergies), (c) climate change adaptation (e.g., increased use of air conditioning), and (d) climate change mitigation (e.g., increased building energy efficiency). [71]; summarizing [44]; looked at (a) potential direct and indirect consequences of climate change (e.g., increased incidence of extreme events, increased temperatures), and (b) potential impacts on the indoor environment (e.g., changes in loads on HVAC systems, damage to and degradation of building materials, increased indoor ozone levels, flooding and water damage, greater use of pesticides) with potential impacts on health. A full taxonomy of potential effects would be conceptually and practically difficult, not to mention nascent, since we may likely see effects not yet seen or predicted in our experience with climate and buildings. Nonetheless, some key implications are described here.

Climate variables (e.g., temperature, precipitation, water vapour, wind speed and direction, cloud properties) can influence indoor air quality both directly and indirectly. For instance, increased outdoor temperatures can lead to increased ozone concentrations, and subsequent reactions that generate pollutants indoors. Increased indoor temperatures can increase chemical off-gassing rates from indoor materials. Increased precipitation can increase risk for flooding and water damage. Climate change can also affect patterns of floods, droughts, wildfires, pests, and vegetation, and related indoor exposures to mold, dust, bacteria, combustion products, chemical pollutants, particulates, pesticides, and pollen.

Climate change mitigation and adaptation measures can also affect indoor air quality. For instance, measures to reduce energy use can lead to lower ventilation rates, tighter buildings, increased reliance on air conditioning, and less use of open windows, which can increase pollutant concentrations indoors. Climate-related hazards can drive people to spend more time indoors, which can potentially increase indoor pollutants, such as through increased indoor activities and product uses that generate pollutants.

While climate change has effects on many types of buildings, especially relevant to green buildings are effects related to energy efficiency measures. These include tighter buildings, weatherization, and less use of natural ventilation. As indicated by Ref. [60]; perhaps more important than the effects directly from climate are the effects that are mediated by humans in response to climate changes. A major effect is reduced ventilation rates due to mitigation measures to save energy, and greater reliance on heating, ventilation, and air conditioning systems, and less reliance on open windows. While reduced ventilation can reduce infiltration of pollutants from outdoors to the indoors, it can also increase concentrations of pollutants indoors. The importance of reducing sources of indoor emissions is even more pronounced.

In conclusion, climate change can create specific challenges for green buildings through increased demands for energy efficiency, combined with changes in outdoor air pollutants, extreme weather events, and mitigation and adaptation measures that can affect IAQ.

1.8. What immediate actions could promote higher IAQ in green buildings?

While it may be thought that indoor air quality problems are ineluctable, to the contrary, some immediate actions can improve indoor air quality. The net benefits of specific actions depend of course on the specific building and the sources of pollutants. Also, any action can have a range of effects, and the direct and indirect implications need to be considered before implementing measures. While the literature abounds with recommendations for improving indoor air quality (e.g.,. [66,72,73], this section discusses some actions that can be introduced at once, are likely to provide overall beneficial effects, and that may not already be included in green building schemes.

One important action would be to focus on pollutant exposure reduction in buildings. Currently, all schemes award ventilation as the major method related to indoor air quality, while exposure receives relatively little attention. Ventilation, although important, may not always provide the desired effects, such as in areas with high outdoor pollution or episodic and uncontrolled release of pollutants (e.g. Ref. [17]. Ventilation may not be effective either for some pollutants, such as SVOCs [58]. Therefore, green building schemes that provide credits only for ventilation may not ensure favorable IAQ. Instead, with a focus on exposures, including actions for source control and reduction, green building schemes could encourage effective methods for reducing risks to human health, which is a goal of improving IAQ.

Another immediate action that could produce benefits would be to reduce compounds that are among the most prevalent and dominant of indoor air pollutants (e.g., [19,20,39,50]; namely, fragrance compounds emitted from products. Fragrance-free policies, which restrict the use of fragranced products, have been implemented in building environments around the world, such as schools, workplaces, hospitals, and public buildings. For example, the US Centers for Disease Control and Prevention, Indoor Environmental Quality Policy [84] states: “Scented or fragranced products are prohibited at all times in all interior space owned, rented, or leased by CDC … Personal care products (e.g. colognes, perfumes, essential oils, scented skin and hair products) should not be applied … CDC encourages employees to be as fragrance-free as possible … Employees should avoid using scented detergents and fabric softeners on clothes worn to the office … " and other measures, which apply to more than 15,000 employees. A recent survey of the US national population [74] indicated that a majority of the general population would prefer that workplaces, health care facilities and professionals, hotels, and airplanes were fragrance-free. Further, more than one-third of the general population reported adverse health effects, such as migraine headaches or asthma attacks, from exposure to fragranced products, indicating the magnitude of potential benefits from a fragrance-free policy.

Another action to promote IAQ in green buildings would be the requirement of indoor air quality guidelines or threshold concentrations for pollutants of concern. For example, the World Health Organization (WHO) issues guidelines for air quality, some of which are regularly updated [90–92]. These guidelines or other well-documented and recognized references could become a fundamental element in certification schemes. Another approach would be the development of standards for IAQ in green buildings, taking into consideration health guidelines for exposure to pollutants.

Additional strategies for source reduction and control include the following: use alternative pest management, such as physical controls without chemical pesticides; implement a healthier cleaning program, as well as nonchemical methods for cleaning; switch to low off-gassing furnishings and materials; install appropriate air filters, which may be common, but also water filters to reduce exposure to volatilized compounds; maintain HVAC systems, including filter check and replacement; and require more frequent monitoring of indoor air quality and surveys of occupant well-being.

In conclusion, given that products and practices indoors are a primary influence on IAQ, actions that target those areas can provide a relatively straightforward way to improve and monitor IAQ. A focus should be on overall exposure reduction, such as source reduction and control, rather than solely ventilation.

1.9. Longer term, how can green buildings be improved to promote better IAQ?

A range of actions can enable certification schemes to more effectively promote IAQ in green buildings. One development would be the definition of an index or metrics of IAQ in buildings. Without discussing whether the development of such an index is at all possible, it is worth mentioning that the lack of such an index is a reason why ventilation, and CO_2 concentration (a proxy for ventilation effectiveness in the presence of people), are used to assess IAQ. It is also worth mentioning that there were attempts to develop such an index in the past. For examples, the levels of dissatisfaction with acceptability of indoor air quality as expressed by the building occupants [33] as well as total volatile organic compounds (TVOC) [59,68] were proposed as metrics of IAQ, among others. However, the TVOC was shown to be a poor predictor of the effects on humans [5]. The former approach still creates the reference for estimating ventilation requirements for achieving acceptable indoor air quality [8,27]. Despite these attempts, developments of IAQ metrics can continue, and could address not only pollutant levels and exposures, but also their effects on building occupants.

In addition, to properly manage and characterize IAQ in green buildings, it may also be beneficial to require emissions testing of all building materials, furnishings and equipment both before and during their use in green buildings. To this end, green buildings may require regular or even continuous measurements of IAQ. Such monitoring would allow remedying unacceptable pollutant levels and sources as well as provide data for building recertification. IAQ recertification of green buildings could become another requirement in certification schemes to assure that favorable IAQ levels are attained and maintained.

In conclusion, the following long-term actions can help promote favorable IAQ in green buildings: (1) Requiring indoor air quality guidelines for key pollutants and awarding credits for their reduction or avoidance; (2) Developing an IAQ index or metrics; (3) Requiring or awarding credits for emission testing of products used in green buildings; (4) Conducting monitoring of IAQ in green buildings; (5) Accounting for cross-category impacts of solutions in other categories on IAQ; (6) Requiring regular recertification based on IAQ levels; and (7) Overall, developing incentives to improve IAQ and in ways that benefit building occupants, employers, and owners, and that create higher recognition of IAQ in green building projects.

1.10. What are the research gaps related to green buildings and IAQ?

Strengths and deficiencies of current green certification schemes relative to IAQ have been identified and discussed in this paper. This section looks at opportunities for research to bridge the knowledge gap between green building practice and potential, enabling green buildings to create and promote better IAQ. The list of research priorities below does not include issues that affect buildings more generally, such as the links between building products and practices, indoor air quality, and health effects. While this research is also needed, the points below are as specific to green buildings as possible.

1. Determine attributes of green buildings that can improve IAQ, and specific actions that can make a building green or healthier relative to IAQ.
2. Evaluate the effectiveness of existing and new credits for promoting IAQ in green buildings, and the relationship between credits awarded and measurable effects on IAQ.
3. Develop key performance indicators, such as acceptable indoor air quality levels, for certification and re-certification of green buildings.
4. Identify green consumer products and building materials that have improved or impaired indoor air quality in green buildings, and investigate their emissions.
5. Assess attributes of green buildings relative to IAQ as expected and rated by the building occupants.
6. Conduct controlled comparative studies of IAQ in green buildings with matched conventional buildings, and controlled intervention studies of conventional buildings converted into green buildings, and measure differences in IAQ.

2. Conclusion

Green buildings have the potential to promote more favorable indoor air quality. On balance, based on available but limited data, perceived IAQ is better in green buildings than in conventional buildings. However "green" does not necessarily guarantee good indoor air quality. Certification schemes may provide inadequate incentive in the credit system for improving indoor air quality. Also, certain green practices and green products could actually impair indoor air quality. The focus on ventilation as a primary method for IAQ control overlooks opportunities for source control and exposure reduction. Given that people spend most of their time indoors, and that people are the most valuable asset in a building, it seems practical and prudent to make investments in overall green building programs and individual buildings to ensure healthful IAQ.

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