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Indoor air quality and its effects on humans—A review of challenges and developments in the last 30 years

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ABSTRACT

A reflective approach is adopted in analyzing the reviews on the impact of indoor air quality on humans over the last 30 years (1986–2016). The major findings reiterate the concerns of indoor air pollution (IAP) and provide a deeper understanding of how contaminants contribute to, and interact to accentuate the adverse effects on humans. Issues which have emerged and increased in importance are indoor chemistry, airborne infection, and the impact on performance. Societal trends of rising affluence of the middle class, increased population density in cities, introduction of new synthetic materials, reliance on childcare facilities have led to greater intensity of exposure to IAP. Responses to climate change, energy conservation and singular strategies to manage the complex challenge of IAP have not been effective in alleviating the deterioration of indoor air quality. Innovations in air distribution, air cleaning, modularization of indoor environmental devices/systems, and leveraging on smart technologies and sensing systems which incorporate algorithms that optimizes indoor air quality with conventional performance indicators are important advancements towards a holistic solution. User engagement, both as a sensor and indicator of preferences, when integrated with such innovations, may usher in the next important paradigm towards achieving acceptable indoor environmental quality beyond the current definitions of acceptability from population-based criteria to one that embraces the individual on an as-needed, when-needed and as-preferred basis.

1. Introduction

Over the last 30 years, there have been significant developments, both in the intensity with which indoor air quality (IAQ) is being challenged, and in the understanding of the interactions and causalities among the various parameters that impact on indoor air quality. The evidence of the impact that IAQ on people makes compelling consideration for its enhancement to mitigate against adverse health consequences, improve quality of life and the work environment with consequential benefits to wellness and performance.

In recounting the history of IAQ, Sundell [1] reiterated that indoor air is a dominant exposure for humans, but has been a rather late consideration against earlier environmental issues such as energy use, sustainability and outdoor air quality. The earlier, and continued focus on outdoor air pollution may be attributable to at least the following observations. Firstly, population-wide adverse health effects associated with outdoor air pollution, in terms of morbidity and mortality, are of a large magnitude in the developed world as reported in episodic incidents such as the infamous London smog [2] and several studies of chronic exposure in cities [3,4]. Secondly, population-wide health statistics and air pollution data are more readily available compared to that associated with indoor air pollution. Thirdly, there have been significant changes in the composition and nature of indoor air pollutants as a consequence of changes in construction materials, consumer products used indoors and building operation that has resulted in characterizing indoor air pollution exposure a complex phenomenon [5]. Fourthly, knowledge of the effects of indoor air pollution on people has been a relatively recent and rapidly evolving one.

IAQ is a multi-disciplinary phenomenon, and is determined by the many pathways in which chemical, biological and physical contaminants eventually become a portion of the total indoor environmental composition. There is spatial and temporal heterogeneity [6] of these contaminants, and the determination of exposure is difficult because of the diversity of time which occupants spend within the space. Furthermore, it is known that some of these contaminants interact [7] even humans participate through the dermal layer (skin) and their clothing [8,9].

The indoor environment is dynamic, being influenced at least by the following:

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- materials (wall finishes, furniture, fabric) that potentially emit or absorb depending on motivating environmental parameters such as temperature, surface air velocity and humidity;
- equipment and processes that may generate pollutants;
- heating/cooling processes, ventilation and air distribution that mix the air, often with turbulence, and also generate flow paths that carry contaminants and facilitate exposure;
- occupant movement and activities that may generate pollution, and re-suspend deposited particulate matter;
- even the presence of humans which contribute bio-effluents, respiratory contamination (especially if they are infectious) [10,11].

Such complexities make IAQ a difficult challenge to address holistically. Understanding of IAQ has proceeded mainly along the more conventional "component" disciplines in chemistry [12–15], thermo- and fluid dynamics, material science [16,17]; its effects on humans have been examined from epidemiology [18–20], psychology [21], productivity/performance [22–24], wellness [25,26] and infection (airborne disease transmission) [27]. Exposure to indoor environments span the entire lifespan: from homes through child care facilities, schools, transport and work premises, shopping malls, hospitals, institutional buildings and even old age/nursing homes. Even at the fetal stage, the foetus is exposed to the biochemical accumulation of the mother which is now inherited through blood [28–31]. The ability to cope with exposures also depend on the development of the immune system, and several works have implicated impairment to health through early, and continued exposures [32,33].

Meanwhile there have been several trends in society that renders IAQ a priority to be addressed [34]: economics has driven the rise and growth of cities leading to high population densities; family participation which necessitated the dependence on child-care facilities; energy efficiency; rise of air-conditioning; climate change; new materials and products. These accentuate the exposure to indoor air pollutants.

This review takes a reflective look at these trends and evaluates their implications on IAQ, the effectiveness of solutions in mitigating them and the challenges that need to be addressed. To understand the challenges, a summary of reviews on IAQ undertaken between 1986 and 2016 are presented – this informs the state of understanding which is then utilized in discussing the implications of the societal trends, and the challenges that need to be addressed. The scope of this review excludes IAQ challenges in developing countries where the issues of exposure to biomass combustion have been well documented [35–41].

2. Summary of reviews

Several reviews have documented the adverse impacts of exposures to indoor air pollution (IAP). This is summarised in Table 1. In summarising the reviews, the salient issues and the evolution of new issues on an approximate chronical sequence is presented. This provides a sense of the emergence of new knowledge about IAP and their effects on humans.

Samet et al. [18,19] reviewed 413 published articles and described several major IAPs in terms of their sources and eventual exposures, and their health effects. From the large number of pollutants found indoors, they identified the following as the most significant pollutants to which exposure presented the greatest concern: tobacco smoke, nitrogen dioxide, carbon monoxide, woodsmoke, biological agents, formaldehyde, volatile organic compounds and radon (and their daughters). Three environments were distinguished, namely the home, office and transportation. Sources differ among them with commensurately different exposures. The home presents a large number of sources including smoking, gas stoves, woodstoves, building materials, earth radon, furnishings and household products, gas-fuelled space heaters, insulation and moist materials. In the office, sources include smoking, building materials, furnishings, copying machines and air-conditioning systems. In transportation environments, these include smoking, ambient air pollutants and air-conditioning systems.

It is notable that several pollutants are common, though their levels are different. Active smoking, an individual choice, leads to involuntary smoking which increases the frequency of chronic respiratory symptoms and reduces the level of lung function in children, and has been implicated as a cause of lung cancer in adults. Exposure to nitrogen dioxide and carbon monoxide, mainly from cooking, is small. The exposures may be accentuated by proximity to traffic sources. There is a diversity of biological agents which are resident in building materials and spread via the air distribution system. Various conditions have been reported, including hypersensitivity pneumonitis, fungal infections and on rare occasions Legionnaire's disease. Chemical emissions, especially of formaldehyde and volatile organic compounds cause irritations but their health effects were inconclusive. It was noted that building related illness, with identifiable etiology, and sick building syndrome (without an identifiable etiology) exist in offices and have been attributed to a variety of causes: low ventilation, VOCs and moisture in building materials.

Control measures suggested include alteration of sources, ventilation and conducting indoor air quality assessments with appropriate remedial actions (Table 2).

The sources are attributed both to outdoor air as well as indoor materials and activities, suggesting that pathways are ubiquitous and eventually rise to significant concentration levels, resulting in chronic exposures.

Based on an examination of 40 published works, Samet [42] reiterated that time-activity and exposure studies demonstrate the dominant contribution of the indoor environment to IAP exposures, the mounting epidemiological evidence of its adverse effects, that risk assessments implicate indoor carcinogens as a substantial contribution to population's burden of lung and other cancers, and that unacceptable indoor air quality is a common cause of the sick building syndrome. A schema for categorising the adverse effects of IAP that straddles perception, symptom response, physiological impairment to increased risk, and exacerbation, of disease and clinically evident diseases is presented. This schema would be useful in defining a societal metric for describing the magnitude of the problem of IAP.

Berglund et al. [20] undertook a commission by the European Concerted Action titled "Indoor Air Quality and its Impact on Man". They adopted a systemic analysis of mainly European and some US based studies, and referenced heavily on World Health Organisation's literature on indoor air quality, and observed the following effects:

- respiratory – children are particularly affected (clear link);
- immune – allergy to dust mites (clear link);
- skin and mucous membranes especially to formaldehyde (clear link);
- cardiovascular – not well documented;
- liver, kidney and gastro-intestinal – not well documented;
- cancer –link to exposure to environmental tobacco smoke and radon and its daughters;
- sick building syndrome – suspected to be attributed to various chemicals which cause sensory irritation or invoke effects on the central and peripheral systems

Examining mainly epidemiological evidence, Jones [43] adopted a similar approach to Samet et al. [18,19] but provided a few additional pollutants and processes that reflect the research under-

Table 1
Reviews on Impact of Indoor Air Quality on Human Effects (in approximate chronological order).

Reference	Scope of review	No of papers referenced	Main conclusions	Recommendations
Samet, Marbury and Spengler [18,19]	Summarises health effects of IAP from literature up till 1986. IAQ assessment, control technology, research needs and clinical implications	413	Evidence of varying degrees of health effects.	Methodology • Total personal exposure, adequate sampling size • ETS – consider involuntary exposure • Radon – more exact quantification of exposure • BRI – define clinical dimensions and causes
Berglund et al. [20]	Human health effects linked to indoor air pollution in homes and non-industrial environments: • Respiratory system • Allery • Immune system • Skin and mucous membranes • Cardiovascular system • Liver, kidney and gastro-intestinal	23	Clear relationship reported with exposure to indoor air pollution (IAP): • Respiratory disease (children) • Allergy (particularly to house mites) • Mucous membrane irritation (particularly to formaldehyde) • Any chemicals encountered indoors are known or suspected to cause sensory irritation, SBS symptoms and affects central or peripheral nervous system leading changes to behaviour and performance • Increased risk of developing lung cancer through ERS exposure • Effects on reproduction, cardiovascular disease and other systems/organs not well documented	• Improve building and HVAC design • Study role of Infection on SBS • Study impact of indoor allergen levels • Risk assessment of indoor carcinogen exposure • Development of more accurate methods of irritation measurement • Evaluating Sensory and nervous system effects • Study impact of indoor exposure on cardiovascular and systemic organs
Mendell [48]	Epidemiologic studies (1984–1992) on work-related symptoms. Focussed on symptom prevalence and factors/environmental measurements	37	Work (office) related symptoms are common and some of these symptoms are preventable through better control of environmental conditions and exposures • environmental factors: increased symptoms with air-conditioning, carpets, higher occupant density, VDT use and low ventilation rates (< 10 L/s.p), high temperature and low RH • personal factors: symptoms increased for female gender, job stress/dissatisfaction and allergy/asthma • multi-factorial problem	Need for good study design: • experimental better than observational • adopt crossover strategy • control for confounding
Samet [42]	Published literature on adverse health effects of IAP in developed countries Adopts a health effects classification system: • Clinically evident • Disease exacerbation • Increased disease risk • Physiological impairment • Symptom responses • Perception of unacceptability of IAQ • Perception of exposure to IAP	40	• Time-activity and exposure studies demonstrate dominant contributions of indoor environments to population exposures to IAP • Mounting epidemiological evidence documents adverse effects of IAP • Risk assessments indicate that indoor carcinogens may contribute substantially to population burden of lung and other cancers • Unacceptable IAQ as common cause of SBS symptoms	Adopt a schema of classification for better understanding of the issues

Table 1 (*Continued*)

Reference	Scope of review	No of papers referenced	Main conclusions	Recommendations
Husman [49]	Health effects of indoor micro-organisms categorised as: • irritative symptoms • respiratory infections • allergenic diseases • alveolitis and organic dust syndrome • other chronic pulmonary diseases	95	Adverse health effect of mold exposure in moisture-damaged buildings Individual factors affect response and symptom presentation Exact inflammatory and immunologic processes behind association between mold exposures and allergy largely unknown.	Identification of microbial strains on surfaces rather than total count. Intervention studies needed on effect of exposure reduction after building remediation
Jones [43]	IAP and health Non-biological sources • Asbestos, CO2, CO, HCOH, NO2, Radon, RSP, ETS, VOC Biological sources • Allergens, fungi, bacteria, viruses	263	Indoor pollutants emanate from: • many sources: biological and non-biological • processes: building design to improve energy efficiency; synthetic materials SBS linked to poor IAQ Health risks from IAP less known compared to outdoor air pollution	• Research into interdependencies and interactions of pollutants • Protocols and analytical methods should consider the whole range of pollutants • Refine understanding and measurement of health impacts • Legal and regulatory aspects require careful considerations • Building design and emission control required
Bornehag et al. [51]	Evaluate association between dampness in buildings and health effects (respiratory symptoms, asthma and allergy)	118	Dampness in buildings increase risk of health effects in airways (OR 1.4–2.2) Dampness associated with other symptoms (tiredness, headaches and airway infection) Causal association between dampness and health effects are strong; however mechanisms are unknown	Preventive measures should be taken against dampness in buildings
Sundell [1]	Reflective approach on exposures with emphasis on environmental issues and building factors (ventilation, materials, indoor air chemistry) and their impact on health	24	Exposure to IAP causes excessive morbidity and mortality • allergies • hypersensitivity reactions • airway infections • cancers Dampness, low ventilation rates and plasticizers are implicated	Multi-disciplinary paradigm needed to provide a total perspective
Mendell and Heath [69]	IAP and thermal conditions on performance and attendance in schools and working environments	183	Direct associations for: low ventilation leads to lower performance and attendance Indirect associations: • Indoor dampness and microbiologic pollutants linked with asthma exacerbation and respiratory infection	Action to improve IEQ in schools to prevent dampness, inadequate ventilation and excess exposure to NO2 and HCOH
Li et al. [86]	Role of airborne transmission of infectious agents in the built environment	40	There is strong and sufficient evidence to demonstrate the association between ventilation, air movements in buildings and the transmission/spread of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox and SARS. There is insufficient data to specify and quantify the minimum ventilation requirements in hospitals, schools, offices, homes and isolation rooms in relation to spread of infectious diseases via the airborne route.	• strong need for a multidisciplinary study in investigating outbreaks and the impacts of the air environment on the spread of potentially airborne infectious diseases. • Such an approach would allow the combined use of the available molecular biology test methods and the new computer modelling and experimental methods for investigation building ventilation.

Table 1 (*Continued*)

Reference	Scope of review	No of papers referenced	Main conclusions	Recommendations
Mendell [54]	Epidemiologic literature on associations between indoor chemical emissions and respiratory health/allergy in infants/children	103	Strong associations Risk factors: HCOH, phthalates, recent painting; renovation, new furniture, carpets and textile wallpaper	Important to confirm and quantify risks ad to guide preventive actions
Weschler [5]	Changes in indoor pollutants since 1950s and human exposures	234	Health risks from indoor pollutants in 2008 differ from those in the 1950s: • Exposure to known and "reasonably anticipated" carcinogens and some toxicants have decreased • Exposure to suspected endocrine disruptors have markedly increased Changes in indoor emissions of volatile pollutants (inorganic gases, VOCs and VVOCs) have impacted indoor environments faster than the less volatile pollutants (SVOCs, heavy metals, fibres)	• Establish monitoring networks that provide cross-sectional and longitudinal information about the state of pollutants in representative buildings. This would enhance knowledge and understanding of the chemicals that are daily inhaled, ingested and absorbed.
Weschler [15]	Chemical reactions among indoor pollutants: gas-phase; surface; health effects	258	• ozone chemistry received most attention: with terpenoids in gas-phase and surface chemistry with common materials, furnishings and humans • surface chemistry have a larger impact on indoor settings than do gas-phase processes	Research needs: • decomposition of common indoor pollutants • how sorbed water affects surface reactions • identification of short-lived products of indoor chemistry • impact of indoor chemistry on health and comfort
Fisk [96]	Potential health consequences of climate change that affect IEQ in residential homes in US and Europe: frequency and severity of heat waves, severe storms with sea level rise, wild fires, increases in ozone	122	Potential adverse health effects: • doubling of heat related deaths • increased hospitalization for asthma, pneumonia and cardiovascular effects during wildfires • increased mortality and hospitalization associated with ozone	Mitigations: • roof insulation • roof coating to reflect solar radiation • more air conditioning to reduce indoor overheating • improved particle filtration efficiency

taken. Ozone and sulphur dioxide were included, though little description was given to ozone, a chemical which would rise in prominence at a later stage of the research in IAP. Allergens related to domestic pets (dogs and cats) are now included, which later studies [44] have provided evidence that they are increasingly becoming a source of allergens that potentially spread among children in child care facilities. It documented further evidence on the sick building syndrome implicating VOCs [45], low ventilation [46] and multiple chemical sensitivity [47]. Jones [43] concluded that IAP continue to be a dominant exposure that has strong epidemiological evidence of adverse effects, and suggested that further research be undertaken into the interdependencies and interactions of pollutants and a holistic measure is necessary. The importance of this approach in shedding further light on the complexity of the chemical exposure pathways is subsequently reiterated [11]. Caution is given that legal and regulatory aspects need careful consideration in meeting the challenges and resolving the uncertainties associated with indoor air quality problems.

Mendell [48] examined the epidemiologic studies on work-related symptoms, focussing on symptom prevalence and factors/environmental measurements. He observed that environmental and personal factors influence prevalence differently. Symptoms increased with air-conditioning, carpets, higher occupant density, video display terminal (VDT) use and low ventilation rates (<10 L/s.p), high temperature and low RH. On personal factors, symptoms increased for female gender, job stress/dissatisfaction and allergy/asthma. He concluded that the problem is multi-factorial problem. Though work (office) related symptoms are common, some of these are preventable through better control of environmental conditions and exposures.

Focussing on indoor micro-organisms, Husman [49] reviewed 95 articles and categorised their health effects as:

- irritative and non-specific symptoms – affecting respiratory tract and eyes as well as manifesting as fatigue and nausea. They are usually associated with mold growth in water-damaged and damp buildings;
- respiratory infections – usually higher in exposure to building mold, and caused by common respiratory pathogens, viruses causing common cold and flu, and secondary bacterial infections such as sinusitis or acute bronchitis;
- allergenic diseases – caused by allergenic molds leading to allergenic rhinitis, asthma and allergenic conjunctivitis. Dampness is

Table 2
Other reviews related to Indoor Air Quality other than Human Effects (in approximate chronological order).

Reference	Scope of review	No of papers referenced	Main conclusions	Recommendations
Cooke [125]	Sources and impact of indoor air pollutants on health in non-industrial environments	37	Indoor air pollution can be an important factor in human health Many toxic substances are more concentrated in indoor air than outdoor air Presence of toxic substances in human breath	Research needed to determine magnitude of impact of indoor air pollution on health
Brown et al. [127]	Reviewed 50 studies for which indoor concentration of VOC were measured between 1978 and 1990	67	Mean concentration of Individual VOCs in established buildings < 50 $\mu g/m^3$ with most below 5 $\mu g/m^3$. Mean concentration in new buildings much higher, by an order of magnitude. Attributable to building materials Predominant VOC in real buildings differ markedly from VOC mixture used for human exposure studies in controlled experiments Definition of TVOC is unclear, making interpretation of effects difficult	nil
Brager and de Dear [121]	Thermal adaptation distinguishing air-conditioned and naturally ventilated environments. Examines climate chamber and field data.	135	Thermal adaptation attributable to 3 processes: behavioural adjustment; physiological acclimitization; psychological habituation (or expectation) Slower process of acclimitization is not so relevant to thermal adaptation in relatively moderate conditions in buildings, whereas behavioural and expectation have a much greater influence. Past thermal history and perceived control are important discriminators of thermal comfort in AC versus NV buildings.	More open dialogue between proponents of adaptive and “heat balance” approaches to thermal comfort: • Improved predictive models and standards • More sophisticated and responsive environmental control Enhanced thermal comfort and energy savings
Fisk and de Almeida [129]	Examines sensor-based demand control ventilation (SBDCV)	43	SBDCV has 2 advantages: (i) better control of Indoor pollutant concentrations; (ii) lower energy use and peak energy demand. Most cost effective when: • Single or small number of pollutants dominate • Large buildings or unpredictable occupancy or pollutant emission Climates with heating or cooling loads or expensive energy cost	nil
Haghighat and de Bellis [126]	Effect of temperature, humidity and surface velocity on material emission rates	66	• Temperature and humidity have significant impact on TVOC emission rates of paint and varnish • Temperature: TVOC emission profile influenced by compounds found in abundance; thus TVOC is not indicator for IAQ RH: fluctuations significant and no trend can be established	nil

Table 2 (*Continued*)

Reference	Scope of review	No of papers referenced	Main conclusions	Recommendations
Monn [6]	Spatial heterogeneity and exposure to suspended particulate matter, NO2 and Ozone	222	Suspended PM is complex with respect to particle size, chemical composition and its sources. Sources of indoor particles are from outdoors, indoor sources and resuspension Air chemistry important for NO2 and O3 There is no general recommendations on the use of specific exposure measurement: depends on study design and hypotheses	Source-attributed particulate concentration is most promising for a comprehensive risk assessment
Destaillats et al. [128]	Indoor pollutants (VOCs, ozone, PM, SVOCs) emitted by office equipment: computers, printers and photocopiers	50	Link between office equipment emissions and indoor concentrations well established for some pollutants including organophosphate flame retardants Personal exposures may be significantly larger than estimated through average indoor concentrations due to proximity and extended periods	Magnitude of emissions, link from emissions to personal exposure, the toxicological significance of the chemicals emitted, and the costs and impacts of alternate materials should all be considered in order to evaluate potential importance of human exposures and health risks.
Batterman and Burge [130]	HVAC system as emission sources affecting IAQ	82	Several HVAC components are sources: • moisture related biological growth or poor humidity control • dust accumulation/fibrous insulation • entrainment, migration and infiltration of contaminants	Good design and operation including pressurization and maintenance (including filters) are essential
Zhang YP et al. [111]	Fan-driven air-cleaning technologies for improvement of IAQ: HEPA, adsorption, UVGI, PCO, TCO, plasma, botanic air cleaner, ion generators, electrostatic precipitators	59	• No technology effectively removes all indoor air pollutants; some generate undesirable by-products Particle filtration and sorption of gaseous pollutants are most effective	A labelling system accounting for characteristics such as CADR, energy consumption, harmful by-products and lifespan is needed
Luengas et al. [112]	Reviewed indoor air treatment technologies: HEPA, membrane, adsorption, UVGI, PCO, TCO, plasma, botanic air cleaner, ion generators, electrostatic precipitators	139	Universal technology for indoor air treatment not available. Combination technologies are being explored.	Combination technologies are promising
Wei et al. [97]	IAQ requirements in green building certifications	69	IAQ is taken in account in all green building certification schemes. Average weightage accorded to IAQ is 7.5% Main IAP considered: HCOH, VOC, CO2 Ozone and SVOC mentioned in <6.7% of certification schemes Recommended IAQ management: emission source control (mentioned in 77%); ventilation; IAQ measurement (mentioned in 65%)	Harmonize different approaches used.
Kumar et al. [120]	State of the art in IAQ sensing	84	Real-time sensing important to provide spatial and temporal variations in IAQ: • accurate information for effective control development of standards and regulations to offer better protection of occupants	Real-time sensing technologies needed.

Table 2 (*Continued*)

Reference	Scope of review	No of papers referenced	Main conclusions	Recommendations
Melikov [114]	Advanced air distribution methods	69	• Total volume air distribution principles are inefficient • Demand ventilation improves comfort and health: as-needed, when-needed, with control over micro-environment	• Need for advanced air distribution that is demand and performance-based. • Collaborative research for holistic solution.

implicated as an environmental factor that result in such mold growth;

- alveolitis (hypersensitivity pneumonia) and organic dust syndrome – caused by any biological dust that has particles <10 μm in aerodynamic size. Alveolar deposition rate is highest for particles around 3 10 μm in aerodynamic size;
- Chronic bronchitis – increased risk is associated with dampness.

These findings confirms that reported by Burge [50]. That water-damaged building materials or dampness is a strong contributing environmental factor is later reinforced by findings from the NORDAMP [51] and EUROEXPO [52] studies. Husman [49] recommended that because of the specificity of the effects, identification of microbial strains on surfaces rather than total count is important.

Subsequently, Bornehag et al. [51] selected 61 studies and classified them as studies of (i) self-reported dampness and self-reported health; (ii) self-reported dampness and clinical examination; (iii) objective signs of dampness and self –reported health; and (iv) objective signs of dampness and clinical examination. The study concluded that:

- dampness increased the risk of health effects in the airways, such as cough, wheeze and asthma relative risks in the range of odds-ratio, OR, between 1.4 and 2.2;
- there is association between dampness in buildings and general symptoms such as tiredness and headache and of airway infections;
- causal associations between dampness and health effects are strong but the underlying mechanisms are unknown.

Such effects have subsequently been reported elsewhere: in child care centres in the tropics [44], and in homes in Bulgaria [53].

Sources of dampness in buildings are mainly due to leakage of rain or snow into the building, moisture from humans and indoor activities, moisture within building materials and constructions from erection time (arising from lack of protection from rain or insufficient drying), and water leakages. Efforts must be directed to mitigate against dampness in buildings.

Within the home, infants and young children may be exposed to chemical emissions, especially when ventilation is low. Mendell's [54] analysis of 21 studies in the epidemiologic literature indicated associations between many risk factors and respiratory or allergenic effects. Most implicated were formaldehyde or particle board, phthalates or plastic materials and recent painting. Elevated risks include renovation and cleaning activities, new furniture, and carpets or textile wallpaper. Among the chemicals, phthalates or plasticizers represent a very substantial compound that is ubiquitous in the home – from toys to carrier bags and many utensils and containers. The odds ratio of adverse effects of rhinitis, eczema and asthma was significant [55] in a nested case-control study of Swedish children.

The chemical constituents of indoor air, especially of VOCs, have been widely reported [12,56]. However, Weschler [5] provides insight into the changing nature and characteristics of indoor air pollutants that have resulted from changes in building materials and consumer products usage, building design and the operation of the ventilation systems. The body burden of chemicals which have been produced in meaningful amounts only over the last few decades as manifested from blood and urine concentrations [57] correlates with chemical compounds found in indoor dust, suggesting that the indoor air pollutants constitute a significant exposure of concern. The phenomenal rise in the use of air-conditioning [58], especially in high density cities, accentuate the challenges to achieving and maintaining an acceptable IAQ against the penetration of external pollutants and the increased emission rates of indoor pollutants.

More recent work has focussed on the role of ozone as an active reactant with potentially toxic and irritable by-products [7,13,11,15]. Weschler [15] provided a comprehensive summary of the advances in indoor gas-phase and indoor surface chemistry since 1991. Ozone reactions are ubiquitous, participating with a substantial proportion of elements indoors. The reaction time constants are short, and ozone-terpenoids in gas-phase produces a large number of semi-organic aerosols (SOAs) of very small size. Surface chemistry with common materials and furnishings, HVAC components including filters, and more recent evidence of reactions with human skin, hair and clothing suggest that the footprint of the effect of ozone-initiated chemistry is large. Where recirculation is substantially practised, such as in warmer climates where air-conditioning is widely relied upon for a greater part of the day, the dust arrested by filters become ready sources of reaction on impinging ozone brought in as part of the outdoor air for ventilation. Such surface reactions can produce significant amounts of semi-organic aerosols (SOAs) which increases the exposure of occupants to these very small particles [59,60]. Health effects include eye and sensory irritation [61–63], contact and respiratory sensitization [64,65], building-related symptoms [66,67], and particles/plasma DNA scission/oxidative damage [68]. Tham and Fadeyi [65] demonstrated that such ozone-initiated chemistry affects asthmatics adversely. More recently, humans have been shown to be scavengers of ozone in the indoor environment, and the nature and impact of the by-products are largely unknown [10,11]. As population density in cities increase, and driven almost universally by real estate prices, the requirement for commensurate ventilation for such increased occupant density potentially accentuate the exposure, particularly when the outdoor ozone levels are elevated.

Beyond sick building syndrome, higher order effects on human performance have become increasing important. As indoor environments should have human-centricity as a prime consideration, the outcomes of human activities are affected by the underlying mechanisms resulting from IAP exposure. Early work in this direction examined the prevalence of symptoms, perception of and satisfaction with the indoor environment and their associations with measures of performance. Subsequently, research focussed on underlying mechanisms.

Mendell and Heath [69] investigated the impact of thermal conditions and IAP on children's performance and attendance in schools. They examined data from 30 studies, but did not find sufficiently persuasive evidence to establish causal relationships between IAP or thermal conditions in schools and the performance of the students. Several suggestive evidence linking IEQ factors to performance were found:

- higher concentration of NO_2 decreased school attendance;
- low ventilation rate decreased performance.

Performance or attendance are likely mediated through biologic, chemical or particulate pollutant exposures or through thermal conditions. Several studies support the finding that poor or inadequate IEQ deteriorates school children performance [70–72]. The pathways are postulated to relate to thermal conditions, higher concentrations of bio-effluents and pollutants when ventilation is low; such postulations are motivated by the already established health outcomes. Economic analysis taking into account time lost, absenteeism and affected learning shows that investment to improve indoor environmental quality is cost effective.

Apart from absenteeism which serves as a proxy measure, research began to focus on direct evidence of the impact of indoor air quality on human performance with particular interest in productivity outcomes. Fisk and Rosenfield [22] provided analysis suggesting the huge economic loss attributable to loss of productivity due to inadequate indoor environmental quality. Wyon [24] used simulated office work comprising text-typing from a hard copy onto a computer screen, proof reading a printed text into which spelling, grammatical and logical errors were inserted, addition of a column of five 2-digit random numbers, without zeros, printed conventionally as evaluation tests of useful “fragments of cognitive and reasoning skills commensurate with the knowledge-based economy”. Experiments conducted in field laboratories, and later corroborated by field intervention studies [23] demonstrated several effects including:

- poor IAQ can reduce performance of office work by 6–9%, with field intervention results showing decrement can be larger than realistic laboratory situations;
- an approximately linear relationship between the percentage dissatisfied with IAQ and measured decrement in performance [73];
- negative impact of raised air temperature and noise levels [74] on performance which are accompanied by SBS symptoms prevalence such as headaches and fatigue.

Wargocki et al. [73,75] designed experiments involving an extended battery of performance tests (cognitive, creative and short-term memory) and demonstrated adverse impact of increased pollution and ventilation rate on productivity with commensurate manifestations of poorer perceived air quality and SBS symptoms. The associations among them are strong and the several studies consistently affirm the findings [76,23]. Seppanen and Fisk [77] provided a meta-analysis of existing work and has shown quantitative relationships between ventilation rates and short-term sick leave, ventilation rates and work performance, perceived air quality and performance, temperature and performance, and temperature and SBS symptoms, and that a relationship exists between SBS symptoms and work performance.

In these studies, common office furnishing and equipment have been used as sources: carpets [73], computers [78]; filters of air-conditioning systems [79]. The proliferation of such items in buildings suggests that care needs to be taken in their selection operation and maintenance, and that adequate treatment be accorded to render their effects as low as possible.

Underlying mechanisms that bridge the observed deterioration of indoor environmental quality and performance outcomes have been explored using bodily biomarkers. Tham and Willem [80–82] suggested that neuro-behavioural related symptoms (such as fatigue, headache) are manifestations of the sympathetic nervous system as seen by elevated secretions of alpha-amylase. Tanabe and Nishihara [83] measured cerebral blood flow and the constricting effects due to attempts to concentrate at higher temperature leads to fatigue. Their findings were extended by Choi, Kim and Chun [84] who employed electroencephalogram (EEG) as measures of stress when exposed to higher temperature, odor irritants and road traffic noise with consequential deterioration of performance. Observing that asthmatics were more sensitive to lower temperatures, Tham and Fadeyi [65] discussed the plausible mechanisms and suggested that the damaged or denudated epithelial barrier in asthmatics brings the low air temperature in direct contact with the C-fibres relatively easier than non-asthmatics with healthier epithelial barrier. This renders asthmatics to be more sensitive in their nasal perception of air temperature. Clearly, the physiological mechanisms have a role to play in the performance of humans. This knowledge is still emerging and likely to remain an active area of study.

The airborne pathway of infection ha been debated for different viruses. The rapid transmission seen during the SARS (Severe Acute Respiratory Symptom) episodes motivated renewed interest in this pathway. Yu et al. [85] provided evidence for the airborne path for the SARS virus, which is consistent with a rising plume of contaminated warm air in the air shaft generated from a middle-level apartment unit, and the risks for the different units matched the virus concentrations predicted with the use of multi-zone modeling. Li et al. [86] conducted a multi-disciplinary review of literature on infection and concluded that:

- there is strong and sufficient evidence to demonstrate the association between ventilation, air movements in buildings and the transmission/spread of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox and SARS;
- there is insufficient data to specify and quantify the minimum ventilation requirements in hospitals, schools, offices, homes and isolation rooms in relation to spread of infectious diseases via the airborne route.

Evidence for airborne transmission of the influenza virus [87,88] introduces a new dimension to indoor environmental design. Zhu et al. [89] and Morawska [90] described droplet fate and movement in the indoor environment suggesting that human salivary droplets as a highly plausible agent of transmission. Quantifying risk of infection continues to be an active research area as there are implications on regulatory and code considerations that strongly influence the design of the built environment, the ventilation and air distribution systems, as well as appropriate mitigation strategies. Szeto et al. [91] combined engineering and epidemiological information and proposed a method for estimating airborne virus exposures in indoor environments using the spatial distribution of expiratory aerosols and virus viability characteristics. Pantelic and Tham [92] empirically demonstrated that air distribution and patterns within the indoor environment strongly determine the spatial and temporal risks of exposure to simulated cough droplets released from a “coughing machine”. The significance of this finding challenges the use of a single air change rate criteria as the sole determinant for design against infection as it adopts a total mixing (uniform spatial distribution) assumption. Pantelic et al. [93] and Pantelic, Tham and Licina [94] reported the effectiveness of personalized ventilation as a mitigation against airborne transmission from coughs.

3. Implications

These implications from the above reviews and the supporting literature may be summarized as:

- indoor air pollution continues to be a concern that requires more definitive action to mitigate against adverse conditions to reduce the burden of disease and to enhance wellness and productivity;
- human performance is affected by indoor environmental exposure and presents a compelling economic case for investment to achieve good indoor environmental quality;
- sources of indoor air pollutants need to be identified and minimized – direct source control;
- causal factors and pathways of indoor air pollution (indirect) need to be mitigated against;
- adverse effects of indoor air pollutants are multifarious and a holistic approach is needed to be effective in its mitigation;
- indoor air pollution is dynamic and may interact under favourable conditions to produce potentially harmful by-products or conditions;
- airborne transmission is evident for some diseases and plausible for others, and needs to be mitigated against;
- the creation (design), operation and facilities management of indoor environments should take a holistic view of the impact the decisions have on the indoor environmental quality.

Such implications suggest the response side in the quest to achieve better indoor environmental quality. An understanding of the major changes in society over the last 30 years may inform the consideration for action spawned from these implications.

4. Major societal developments that impact IAQ

Several societal developments over the last 30 years have changed the landscape of exposure to indoor air pollutants, thus presenting challenges and consideration for appropriate response to the implications outlined above.

4.1. Measures or initiatives developed and implemented in response to sustainability and climate change challenges

The Institute of Medicine [95] described the impact that climate change has on indoor environments with consequential health outcomes. Outdoor environmental conditions include heat waves, hurricanes, extreme precipitation, sea level rise and flooding, wildfires leading to increase in outdoor fine particles and increased levels of ozone and pollen. The consequences on the indoor environment are periods of extended high temperatures, increase in dampness, lengthier durations of high particle matter, elevated levels of indoor ozone and pollen allergens. From the reviews, these have exacerbated adverse effects on health ranging from thermal stress, respiratory and cardiovascular health effects, allergies and asthma. Fisk [96] identified changes in building design (roof insulation and solar reflective roofs), use of air-conditioning to mitigate thermal effects and better filtration to arrest penetration of PM and pollen as low cost methods to alleviate these adverse impacts. These are not without consequences. Accumulated particles on filters when subsequently exposed to ozone spawns SOAs through surface chemistry. Higher intensification of the use of air-conditioning (partly due to rising affluence of a huge middle class) demands more power to be generated, and the rejection of heat to the environment contributes to the heat island effect [58]. Mitigation measures need consider the whole chain effect and even tough judiciously applied, will find it difficult to avoid the adverse consequences on the indoor environment entirely. It can be expected that climate change will accentuate the adverse effects of indoor environmental quality, either directly or indirectly.

In addressing sustainability, green building assessment schemes have proliferated and strongly influenced the new building stock from design response, and existing building stock as they are renovated to attain certification. Wei, Ramalho and Mandin [97] analysed 31 green building certification schemes and observed that the average weightage accorded to IAQ is only 7.5%. Given this relatively low weightage, it is likely that investment and emphasis for new building stock, and even the retrofitting of existing stock, would gravitate less towards improving the indoor environmental quality than other more prominent dimensions, especially energy efficiency. Emission control, ventilation and indoor environmental assessment are three main strategies recognized by these schemes. As occupant satisfaction and the psycho-social dimensions are substantial influencing factors, these have been suggested to be included [21,26,98]. Increase in weightage accorded to IEQ would encourage definitive action towards attaining enhanced IEQ, as is the spirit of the GreenMark scheme [99,100].

The rise of Zero Energy Building and Carbon Neutral Building have likewise suffered from the low emphasis accorded to IEQ.

4.2. Strong socioeconomic patterns driving urbanization and family work patterns

Continuing powerful trends of urbanization and growth of cities especially in developing countries many of which have large populations have contributed to challenges to its IEQ – increased traffic emissions, densification of population and buildings, transportation environments, higher social contact and high energy intensity. In land scarce cities, where above ground growth has reached its limits, underground construction has become a viable option. The chronic exposures to emissions, bio-effluents, due to high occupant density and human-to-human contact, traffic originated pollution and the synthetic materials have potential consequential adverse health and productivity outcomes. Stress in living and working in cities elevate the population's susceptibility to various adverse reactions to inadequate IEQ as suggested in the reviews.

Airborne and fomite infection opportunities and its spread through the community has emerged to be an important concern. As cities grow and social interactions increase both in quantity and intensity, modelling of their impact on epidemics [101] has shown that the risk of disease transmission would increase with population density and transportation volume. Several studies have demonstrated that respiratory exhalation, coughing and sneezing can carry expiratory droplets up to 6 m for the highest momentum driven expelled droplets [102,103,92]. Airborne droplets may deposit onto surfaces, contributing to the inorganic environmental surface related fomite transmission [104,105].

The increased reliance on childcare facilities is commensurate with the work participation of both parents as a dominant economic norm. Young children are delegated to childcare premises often for durations that are very long, sometimes longer than the time that their parents spend at work. The reviews have demonstrated that these young children are particularly susceptible to indoor air pollution because of their immature immune systems and smaller body weight. The nature of their communal activities result in close social contact and the sharing of toys and various paraphernalia which are vehicles of transmission of bacteria and viruses. Some studies, for examples Zuraimi and Tham [44] and Zuraimi et al. [106], have demonstrated associations and elevated risks of the prevalence of respiratory symptoms (for example, rhinitis and wheezing) with inadequate ventilation, environmental exposure to dampness, chemicals, and dust.

4.3. *Rising economic affluence without commensurate adequately informed consumer choice or consumer protection*

The rising affluence of the middle class is correlated with a higher propensity towards the use of air-conditioning [58]. In many situations, economics and flexibility (modularity) of use, result in the adoption of stand-alone, or clustered, fan-coil systems working with direct heat exchange. Often, these do not have ventilation designed into their function, thus concentrating the pollutants and bio-effluents within the premises. Sekhar [107] demonstrated the rapid rise of carbon dioxide in such a premise, and this may be interpreted as a surrogate indicator of human bio-effluents. Thermal comfort dominates and the reduced odour perceptive ability at lower temperatures [108] makes one less aware of the pollution build-up. With no intentional ventilation, such are situations where sleeping meant to rest and restore the body after a day's activity and stress, is now challenged with a compromised indoor environmental quality.

Travel patterns have shifted significantly, with airplane travel being a common mode. The high passenger density with air circulation patterns that make transmission of infection within aircraft has been highlighted by several studies [109,110]. The airplane has compressed the time scale for global spread of infectious disease to occur.

4.4. *Technological innovation that either ignores or accords little consideration for effects of exposures to adverse indoor air quality*

Technological innovations usually focus on singular or a set of desired performance indicators; their marketing emphasizes particular strengths and is often silent (within the provisions of regulatory frameworks) on adverse implications. Jarl's [29] documentary effectively conveys that the pervasive usage of chemicals in everyday products because of their desirable modifying effects on material behavior (such as flame retardants, surfactants, plasticizers, etc.) has given rise to exposures with significant undesirable long-term effects. Weschler [5] noted a significant shift in indoor air pollutants since the 1950s and concluded that endocrine disruptors have markedly increased, and that there these chemicals correlate well with those found in indoor dust. The study by Bornehag et al. [55] implicated phthalates as a significant pollutant source ubiquitous in homes, and the subsequent studies [44,53] have demonstrated that this exposure is common. The persistence and accumulation of xenobiotic chemicals in the human body have been demonstrated to cause endocrine disruption with potential genetic modification that not only manifest effects in the exposed individuals but are also being passed onto the next generation [28–31]. A more holistic assessment of the innovations and their impact on IEQ would encourage IEQ-friendliness as an essential component of technological innovation.

5. Recent and emerging solutions

Tackling the indoor air quality challenges require a holistic approach. There should be elements of prevention and mitigation, with supporting technologies and social behaviour.

5.1. *Prevention*

Effective prevention stems from a fuller understanding of the underlying issues. This review reinforces the complexity of indoor air quality challenges. The physical, biological and chemical dimensions interact dynamically, and air not only moves, but is the vehicle that facilitates these interactions. The unpreventable contact between air and the surfaces and humans renders the strategy of isolation difficult. At the fundamental stage, source control by adoption of emission labelling schemes exclude potential contaminants. Unless mandated, compliance may vary, often determined by economic considerations and the level of commitment of the parties involved.

External environmental factors are usually not within the purview of the building owner or facilities manager, and they can be considered as impositions to which a building and its systems need to respond to. These vary, and are sometimes affected by episodic occurrences such as elevated ozone, PM and other pollutant levels. Sufficient mitigation in ventilation, air-cleaning needs to be designed for and judiciously operated. As smart technologies take on an increasing role, it is perceivable that smart sensing, enabled with suitable algorithms that incorporate optimization of indoor environmental quality and coupled with appropriate granularity of such air treatment and ventilation technologies will find a greater role in this preventive route.

Pathways of contaminant are complex as indicated from this review. This would also include the dynamics of interactions and reactions that occur, either in the gas phase, or in the surface reactions which has now been evidenced as the more significant mode. The continued use of air-conditioning and air distribution will further propagate the occurrence and spread of contaminants and their by-products within the building. Due consideration on design and material usage, including filters, would be important.

5.2. *Mitigation*

The constraints on preventive measures are influenced by economic considerations; at the building level this will be investment considerations and dependent on the economic returns being used. There are also equipment, processes and activities which in turn are influenced by procurement guidelines and operational requirements. Humans will continue to be a source of contamination. Thus, mitigation measures need to complement the limits that preventive measures can attain.

Technological solutions, particularly in air cleaning, would be needed. However, a recent review on fan-assisted air-cleaning technologies concluded that none is effective in addressing the entire spectrum of pollutants encountered indoors [111]. Luengas et al. [112] examined air treatment technologies and arrived at a similar conclusion and advocated that combination of complementary technologies is needed to achieve desired effectiveness. Matching source characteristics, the potential interactions among indoor air pollutants, and applying the cleaning mechanisms at the different pathways of pollutant generation, transport and deposition is essential. Macro level (such as at the central air conditioning and distribution) and micro level (down to the individual level) may need to be deployed to attain effective and efficient outcomes.

Air distribution innovations have recently been introduced. Melikov [113,114] provides an overview of the developments in this technology and discussed the relative advantages against criteria of energy efficiency, ventilation effectiveness, pollution and infection mitigation. The concept of demand ventilation has been taken down to the individual level. Personalised ventilation has been demonstrated to be an effective and efficient technique that brings conditioned, or where outdoor air quality is deemed acceptable, ventilation directly into the breathing zone of the occupant. The advantages of being able to generate and maintain a personal cloud of cleaner air in the immediate surround of the individual offers protection against impinging aerosols [92–94] and indoor contaminants [115,116]. Further advancement included personalised supply coupled with personalised exhaust [117–119] that increases the effectiveness of removal of expiratory pollution from a sick person when interacting with another (for example a doctor). Such innovations are likely to become important infection control against potential airborne pathways in healthcare facilities and hospitals.

Smart Sensing and smart technologies beckon their development and deployment to provide realtime information in a spatially distributed indoor environment. Because of the variation in indoor contamination, different source locations, strengths and operation, occupant diversity, and also the impact of air distribution patterns, it has become clear that providing mitigation as-needed, where-needed and when-needed would be a paradigm shift to enhancing the indoor environmental quality. A recent review on real-time sensors [120] observed the lag time between exposures and sensing, actuation and management interventions, and advocated the development and deployment of real-time sensors. Such a sensor network, which can become part of the infrastructure of the indoor environment, can provide spatially and temporal information needed for specific, targeted and appropriate mitigation. The modularity of the mitigation technologies must, however, match the actions needed at a spatial granularity. The developments towards this area is promising.

User engagement is perhaps a largely neglected frontier that will become increasingly important. Much is established on how perception and satisfaction of the human in the indoor environment are important determinants of their wellbeing. These are associated with health outcomes of SBS with consequential impact on productivity. Yet most work reported outcomes with humans as a passive receptor of what the indoor environment imposes on them. The effectiveness of engaging the user as an active moderator of the indoor environment has been evidenced through adaptive thermal comfort [121,122]. The role of the human as a dynamic sensor is interesting and offers potentially significant opportunity for achieving a personal indoor environment that is most preferred. Mechanisms for human participation may involve smart technologies of mobile phone applications, computer-based or user interfaces that through industrial design and visual presentation invite participation, or even to wearable sensors that connect with the sensing system. Work which demonstrated skin responses (temperature and perspiration rate), bodily signals (cardiovascular) can be utilised as useful inputs that complement the more consciously provided feedback. This is predicated on design and provision of actuation at a commensurate granularity to achieve the combination of actions that determine that immediate personal environment. Personalized ventilation and heated and cooled chair [123] are examples of such innovations. A wireless sensor-based IEQ system which incorporates user feedback as part of its optimization control will provide the next generation IEQ technology and this is currently being researched [124].

6. Conclusions

The reviews spanning the last 30 years reiterate indoor air pollution to be a major impact on comfort, health, wellness and performance. Factors that contribute to indoor air pollution are ubiquitous, both in the outdoor contaminants brought into the indoors as well as the ever increasing sources that are indoors. Energy conservation and climate change responses potentially accentuate the challenges of acceptable indoor air quality.

New knowledge on the interactions between various contaminants, primarily ozone-initiated chemistry, have shown that the indoor environment itself participates in the generation of IAP. Surface chemistry with almost all that is indoors, including humans, raise concern over potentially harmful by-products and fine particle exposure.

The societal trends of increased population densification, family and work structure, childcare reliance, affluence and consumerism of products that contribute to IAP or are vehicles of IAP exposure have increased the risks of IAP exposure and airborne infectious disease transmission. Of concern are the myriad of chemicals that have been utilized for their specific functional properties (such as plasticizers that render plastic versatile in mechanical properties, flame retardants, non-staining carpets and fabric, grease-resistant wrappers) but which have been implicated for their uptake into human organs that adversely affect development, impairs health and even transmitted to the foetus.

A holistic understanding of the characteristics of sources, their interactions and pathways of exposure is essential to effective mitigation. The combination of preventive and mitigation strategies is needed to effectively address the IAP challenge.

Technological innovations and design enable solutions to be delivered at different scales. And should be thought through as a whole building life cycle consideration. Evidence from health and economic outcomes justify their investment. Innovations of personalized ventilation, and distributed sensing and control leveraging on the penetration and adoption of smart technologies with user engagement may usher in the next important paradigm towards achieving acceptable indoor environmental quality beyond the current definitions of acceptability to one that embraces the individual on an as-needed, when-needed and as-preferred basis.

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