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A review of critical residential buildings parameters and activities when investigating indoor air quality and pollutants

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Abstract

Indoor air in residential dwellings can contain a variety of chemicals, sometimes present at concentrations or in combinations which can have a negative impact on human health. Indoor Air Quality (IAQ) surveys are often required to characterize human exposure or to investigate IAQ concerns and complaints. Such surveys should include sufficient contextual information to elucidate sources, pathways, and the magnitude of exposures. The aim of this review was to investigate and describe the parameters that affect IAQ in residential dwellings: building location, layout, and ventilation, finishing materials, occupant activities, and occupant demography. About 180 peer-reviewed articles, published from 01/2013 to 09/2021 (plus some important earlier publications), were reviewed. The importance of the building parameters largely depends on the study objectives and whether the focus is on a specific pollutant or to assess health risk. When considering classical pollutants such as particulate matter (PM) or volatile organic compounds (VOCs), the building parameters can have a significant impact on IAQ, and detailed information of these parameters needs to be reported in each study. Research gaps and suggestions for the future studies together with recommendation of where measurements should be done are also provided.

KEYWORDS
building parameters, indoor air pollutants, indoor air quality, residential buildings

1 | INTRODUCTION

Air quality is considered to be the most important public health risk factor, especially Indoor Air Quality (IAQ).[1] Research suggests that people spend almost 90% of our time indoors, and on average two-thirds are spent in residential buildings;[2,3] more than half of breathed air is residential indoor air. In addition, vulnerable groups, including children below 3 years, elderly, and chronically ill, spend more time in their dwellings than the average person.[4,5] During the COVID-19 pandemic several lockdowns were implemented worldwide, resulting in most of the global population being confined to their own residences with its indoor air. This fact, combined with the importance of IAQ for sleeping quality and next-day performance,[6–8] emphasizes the importance of research on IAQ in residential buildings.

It is necessary to define the parameters that should be included in any indoor air survey of residential buildings. This is of particular importance because a citizen, designer, builder, or architect, creating the interior environment (i.e., deciding the finishings and furnishings, or the occupants' activities), may directly benefit from evidence and knowledge gathered by IAQ scientists. Better IAQ data quality and data analyses will lead to improved remediation of air quality problems. Moreover, research results from field studies and indoor air measurements are important as decision-making information for the politicians and regulators responsible for building codes and regulations. However, the data must be comprehensive and presented in an understandable and consistent format if legislative and regulatory actions are the goals.

Thousands of articles present results from indoor air surveys in residential buildings and research findings in model houses. However, there are still research gaps and dependences where further studies are needed.

This review is one of the outcomes of the COST Action CA17136—Indoor Air Pollution Network (INDAIRPOLLNET). A literature search on the impact of different parameters on IAQ in residential buildings has been performed. According to the United Nations, a building is defined as *residential* when more than half of the floor area is used for dwelling purposes.[9] There are other definitions but within this COST Action and for the purposes of the literature search, a residential building was defined as a space used for the permanent and temporary residence of individuals. The main aim of this paper was to review previous research studies in relation to the impact of a series of factors to identify the main parameters affecting IAQ. Another objective of the paper was to examine current limitations and research gaps together, making recommendations regarding where to measure IAQ in dwellings. To our knowledge, there is no such previously published study.

Practical implications

Building materials and location, including proximity to outdoor pollution sources, as well as the building ventilation strategy can all have an impact on Indoor Air Quality (IAQ) in residential buildings and should be documented in any IAQ indoor investigation. Occupant indoor activities and details regarding the indoor finishing materials and furnishings also impact IAQ and should be detailed. IAQ should be monitored continuously in critical rooms to ensure that abnormal events and peak concentrations are recorded for correct analysis of any negative effects on occupants.

2 | METHODS

This report reviews studies that addressed the impact of several parameters including building location, building layout, building ventilation, interior finishing materials, occupant demography, and occupant activities (with a section about cooking) on residential IAQ, focusing on chemical pollutants. These parameters were chosen by a multidisciplinary group of experts, who were participants of COST Action CA17136. The indoor location where measurements were collected was noted in the reviewed studies to make recommendations regarding where to measure IAQ in dwellings. Thermal comfort parameters such as relative humidity and temperature are outside of the scope of this review.

Articles published from January 2013 to September 2021 have been included, together with some earlier relevant publications. A systematic search was done using two on-line databases: Science Direct and Scopus, and some additional articles were identified in the references found in the reviews found in the primary search.

The combination of keywords "indoor air" AND "homes" OR "residential" OR "dwellings," AND "chemical pollutants" and the selected parameters were used to perform the searches. In this way more than 16000 different articles were found. Then, since the review was focused on the publications discussing the impact of different parameters, rather than dealing with monitoring of different pollutants in different types of residential premises, detailed searches through the "titles," "abstract," "discussion," and "conclusions" sections of the articles were performed to discharge the papers not dealing with parameter impacts on IAQ. Finally, about 180 articles were identified, based on their relevant content in relation to the selected parameters.

3 | BUILDING LOCATION

The following factors related to the impact on IAQ of residential building location were considered in this review: (1) region (country or region), (2) surroundings (urban, suburban and rural), (3) local direct emissions (road traffic, bus stop, petrol station, industrial, or commercial activities), (4) climate and season (meteorological parameters), (5) topography (influence of altitude and/or air circulations), and (6) proximity to water bodies. However, despite their importance, it was not possible to find publications that considered factors 5 and 6 within the considered period, and consequently, only factors 1 to 4 are included in Table S1.

Most of the recent publications relevant to the influence of the location on IAQ have focused on local surroundings and direct emissions or season or climate. There are fewer studies comparing the influence of location in terms of different regions or countries.

Globally for building location, the three most frequently measured pollutants are particulate matter (PM) with an equivalent aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), nitrogen dioxide (NO_2) and VOCs, followed by carbon dioxide (CO_2), formaldehyde (HCHO), and ozone (O_3).

Most studies measured IAQ in bedrooms and living/dining rooms.[10–17] Other spaces, including kitchens, bathrooms, or other rooms[18,19] were monitored and a small fraction of the studies do not specify where the measurements were conducted.[20–23] In general, most studies have included outdoor air quality measurements.

Indoor Air Quality is strongly influenced by outdoor air quality, usually provided either by natural or mechanical ventilation (MV). Besides the unintentional introduction of primary pollutants into the indoor space, some very reactive secondary pollutants from outside, such as ozone, can also significantly affect IAQ. In some southern European countries, this pollutant can often reach relatively high outdoor concentrations and can play a significant role in IAQ.[24–26] However, most of the research on the impact of factors associated with building location analyses IAQ and its indoor emission sources and, only in a complementary way, studies the possible importance of outdoor air quality on IAQ, which constitutes a gap in research methodology.

Research studies on the impact of the location on IAQ are centered on local sources that can directly and significantly affect the quality of the supplied air by ventilation, being easy to establish a cause-effect relationship. This is the case for major traffic sources or petrol stations in urban or suburban areas or major industrial sources in suburban environments.[27–30]

Previous studies suggest that the indoor pollutants most likely originated from outdoors are $PM_{2.5}$, NO_2 and some VOCs.[17,29,31–33] Moreover, O_3, particles with equivalent diameters of less than 10 μm (PM_{10}) and carbon monoxide (CO) were also included in the studies, but less frequently.[17,31,33] Occasionally, other pollutants such as HCHO, black carbon (BC), Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorinated Biphenyls (PCBs) or Benzene, Toluene, Ethylbenzene and Xylenes (BTEX) were also discussed.[28,30,32,34]

Building ventilation in locations influenced by emissions from major emitting sources, such as petrol stations, bus stops, road traffic, or large infrastructures (airports, ports, thermal power plants, etc.) play a crucial negative role in the IAQ of residential buildings.[28,30]

4 | BUILDING LAYOUT

The impact of building layout on IAQ in dwellings was reviewed (see Table 1) by considering the following factors: retrofit/renovation of building, construction type (hollow block/cavity wall/timber frame, solid concrete/brick wall), age of building, insulation material, building maintenance, glass surface area, floor ratio, room dimensions, presence of garage, basement, swimming pool, and/or restaurant, together with orientation. Again, most studies measured IAQ in bedrooms and living/dining rooms while kitchens, bathrooms and other rooms were studied to a lesser degree, and outdoor air quality was reported. No relevant studies were found within this literature search that focused on factors such as: glass surface area, floor ratio, room dimensions, presence of swimming pool/ spa, building orientation, and restaurant at ground floor.

Given the current international attention on building energy efficiency, several research studies investigated the impact of retrofitting or renovation of buildings on IAQ, indoor environmental quality and in some cases occupants' health. The influence of finishing and renovation of houses on the concentrations of VOCs (including HCHO) and semi volatile organic compounds (SVOCs) varies, depending on the nature of the pollutant, introduction of new materials and room ventilation.[34–38] In general, VOC concentrations increase after retrofits and in the long-term (1 year after retrofit/renovation) a decrease in VOCs and HCHO concentrations is observed.[39–41] Several publications attributed measured indoor pollutants (VOCs, SVOCs) to new high-emitting construction products installed in these houses (insulation materials, wood, and wood-based products) installed during retrofitting activities.[42,43]

Green houses are not always as "green" as expected since the incorporation of "green materials" does not always reduce main emissions, and for airtight buildings this could result in higher levels of indoor air pollutants.[44–46]

The age of buildings has also an important influence on IAQ.[13,41] Newly built residences with low-emitting materials exhibited lower median concentrations of benzene, toluene, $PM_{2.5}$ and radon, compared with levels measured in conventional dwellings where low-emitting materials have not been used.[46] HCHO concentrations were correlated with the age of the building in several studies. Higher HCHO levels were measured in buildings constructed after 1975[47] or 1990 compared to the ones built between 1948-1975 or between 1948-1990, respectively.[17] One reason cited is the increased prevalence of wood frame construction.[41] SVOCs (including flame retardants and PCBs) were also associated with the period of construction of the building, with higher concentrations measured in older buildings (considering only buildings built since these compounds were

TABLE 1 Selection of recent studies on the impact of building layout on Indoor Air Quality in dwellings

Studied factor	Room	Chemical pollutants studied	Ref.
Retrofit/renovation of the building	Living room, kitchen, balcony	HCHO, PM	39
	Child's bedroom (or room where child spent most time)	VOCs, HCHO, $PM_{2.5}$, BC, UFPs, S	35
	Main living area, outdoors	HCHO, CO, CO_2, NO_2, PM, radon	195
	Living area, basement (radon)	VOCs, HCHO, CO, CO_2	196
	Main living room and main bedroom	TVOCs, HCHO, BTEX, CO, CO_2, $PM_{2.5}$, NO_2	37
	Residential rooms	VOCs, HCHO	34
	Main living area, kitchen	VOCs, SVOCs, HCHO, PM	42
	Bedroom, living room, 2nd bedroom, study	HCHO, TVOCs	40
	Living room	TVOCs, PM	69
	Main living area, outdoors	BTEX, HCHO, NO_2, radon	36
	Several (review)	HCHO, VOCs, NO_2, radon	38
	Main living room, master bedroom	TVOCs, HCHO, radon, fungi	65
Green buildings	Personal monitor	$PM_{2.5}$, NO_2, nicotine, HCHO, CO_2	45
	Main bedroom, living room and kitchen	TVOCs, VOCs, RCHO, CO and PM	46
Construction type (hollow block/cavity wall)	Main living room and main bedroom	TVOCs, HCHO, BTEX, CO, CO_2, $PM_{2.5}$, NO_2	37
Age of the building	Main bedroom, living room, kitchen	VOCs, TVOCs, RCHO, CO, CO_2, $PM_{2.5}$, radon	46
	Main bedroom, living room	BTEX, HCHO	47
	Living room, main bedroom	VOCs, RCHO, PM_{10}, $PM_{2.5}$	17
	Living room	TVOCs, PM	69
	Living room, dining room, bedroom	FR, CVMSi	48
	Child's bedroom	SVOCs	30
	Whole residence (vacuum dust collected)	Pb, As, Mn, Ni, Cr, Cu, Zn in dust	197
	Bedroom, living room	PCBs, PAHs	49
		VOCs	13
Room dimensions (volume)	Main living area	TVOCs, PAHs, PM_{10}, UFPs	166
Garage attached to the building	Main bedroom, living room	BTEX, HCHO	47
	Main living area, outdoors, garage	VOCs, CO, NO_2	52
	Living room, main bedroom	VOCs, RCHO, PM_{10}, $PM_{2.5}$	17
	Living room	TVOCs, PM	51
	Undefined	BTEX, NO_2, CO	52
Presence of a basement	Main living area, basement	VOCs	56

Abbreviations: BC, black carbon; BTEX, Benzene, Toluene, Ethylbenzene and Xylenes; CVMSi, cyclic volatile methylsiloxanes; FRs, flame retardants; HCHO, formaldehyde; PAHs, Polycyclic Aromatic Hydrocarbons; PCBs, Polychlorinated Biphenyls; PM, particulate matter; particulate matter with aerodynamic diameter ≤0.1 µm, 0.5 µm, 1 µm, 2.5 µm, 7 µm, 10 µm ($PM_{0.1}$, $PM_{0.5}$, PM_1, $PM_{2.5}$, PM_7, PM_{10}); RCHO, aldehydes; S, total sulfur; SVOCs, semi volatile organic compounds; TVOCs, total volatile organic compounds; UFPs, ultrafine particles; VOCs, volatile organic compounds.

started to be used).[48,49] However, some studies reported that there is no statistically significant correlations between VOCs and the age of buildings.[41] A study of low-income dwellings in the US concluded that infiltration rates in buildings are influenced more by the age and volume of the building than by retrofit activities.[50]

Attached garages have been identified as a factor influencing the IAQ. BTEX, total volatile organic compounds (TVOCs) and NO_2 concentrations were higher in the living areas of these houses.[47,51,52]

5 | BUILDING SYSTEMS FOR VENTILATION, HEATING AND AIR CLEANING

In this section, the impacts of different types of ventilation systems and other related factors are summarized. Studies investigating the impact of ventilation systems on IAQ in residential buildings are summarized in Table S1, and include factors such as ventilation modes (e.g., natural and mechanical), seasons, locations of air vents, window opening and closing status, newly constructed or renovated energy efficient buildings, heating types, air purifiers, heating—ventilation—air conditioning (HVAC) systems and maintenance of HVAC filters.

Ventilation is a key factor for IAQ.[53] In residential buildings with natural ventilation (NV), defined as air driven purely by natural forces, for example, buoyance and wind forces, several studies[17,46,54,55] have shown that seasonal variation can significantly influence the indoor thermal environment and some pollutant concentrations, while others[10,56] have shown that seasonal variation is not so important, especially for pollutants whose main sources are indoor, for example, $PM_{2.5}$ from cooking. The impact of frequency and length of time that windows are open and types of windows on IAQ was studied by several groups.[34,57–62] Concentrations of CO_2 and pollutants such as HCHO and TVOCs can increase when windows are closed, as a result of reduced fresh air ventilation. The positioning of supply air vents, air intakes, exhaust vents and infiltration/ exfiltration paths are all important factors, and incorrect positioning has been shown to result in poor IAQ in naturally ventilated dwellings.[63,64] The air flow rate from NV also depends on weather conditions, for example, the airflow rate is often not high enough in warm weather to provide adequate ventilation.

Ventilation is also a key in providing an improved IAQ in retrofitted energy efficient buildings, especially when MV is provided.[36] Higher concentrations of certain VOCs were detected in conventional dwellings, compared with newly built energy-efficient dwellings with MV.[65] Several studies showed that MV generally provides higher air changes per hour.[36,46,57,63,65–67] However, MV can also bring challenges such as lower RH and increased noise, or its non-use due to the lack of competence when programming.[46] Ortiz et al.[43] reported that a high level of airtightness in retrofitted buildings may increase concentrations of indoor pollutants or dampness, and leads to complaints and health risks for the occupants. It is strongly recommended by authors that the proper functioning and maintenance of the installed equipment (e.g., HVAC, MV, and heating systems) in retrofitted buildings must be assured.

The type of heating system used in the dwelling can also affect IAQ. A strong correlation between indoor air pollutants and type of heating fuel (e.g., coal and wood) was found by Mentese and Tusdibi[10] in Turkey. Generally, indoor fuel combustion can contribute to extremely high $PM_{2.5}$ and CO concentrations,[59] and the indoor $PM_{2.5}$ concentration was high with the use of a wood stove[68] in naturally ventilated dwellings. TVOC concentrations were higher in naturally ventilated dwellings with central heating and solid fuel heating than in dwellings with gas boiler, electric heater (the houses with electric heater were mechanically ventilated) and a heat pump in Slovak Republic.[51] There is a study in Macedonia that addressed the impact of heating systems including central heating, electric energy, wood stove, and heat pump systems on the levels of indoor TVOC, $PM_{2.5}$, and PM_{10},[69] but the types of ventilation system were not described.

Outdoor pollutant loading and its impact on the IAQ has also been studied.[62] In some countries where occupants are challenged by high levels of outdoor PM and VOCs, the use of some air cleaners/filters has been shown to reduce significantly the concentration of fine particle,[70] $PM_{2.5}$ concentration[71] and even achieved 39% lower TVOC concentrations.[72] However, more care is needed before those products are recommended to users because some products do not achieve their claimed performance. Moreover, proper maintenance of the air cleaner is needed, otherwise secondary VOCs can emit from the dirty filters, as reported by Pei and Ji.[73] Popular air cleaners that use photocatalysis and UVC disinfection can generate HCHO and acetaldehyde due to incomplete photocatalytic oxidation.[74] In order to extend the lifetime of an air purifier with good cleaning efficiency, an in-situ thermally regenerated air purifier was proposed by Xiao et al.[75] for removing indoor HCHO. A few mathematical models were developed to estimate the benefits and costs of in-duct activated carbon control of ozone[76] and predict BC concentrations.[77] The efficiency of HEPA filters to remove PM_{10}, $PM_{2.5}$ and respirable suspended PM has been shown to be significantly associated with room volume but not with the age of the building, season, outdoor weather, floor level (multi-floor residential buildings), or the location of the district area.[78]

6 | FINISHING MATERIALS

There are several studies where the impact of finishing materials on IAQ is studied, and they are summarized in Table S1. Current research on the impact of finishing materials on IAQ in dwellings focus mainly on VOC emissions,[34,36,46,54,79–83] with HCHO being the most studied.

Several authors[34,54,80,82,83] have highlighted the important role of floor and furniture material in relation to VOC concentration. Chang et al.[34] concluded that panel-type furniture together with wall decoration were the main sources of indoor HCHO, while wood floor and panel furniture were sources of TVOCs. Huang et al.[82] identified hydrolysis of building materials and furniture as a main source of butyraldehyde. They also claimed that composite wood flooring had stronger VOC emissions than solid wood flooring, except for 1,4-dichlorobenzene.

Recently SVOC measurements have become more important due to their increased presence in dwellings with new materials; they are present in both the gas phase and adsorbed onto dust particles[84–88] (settled dust and airborne particles).

Data analysis methods including PCA (Principal Component Analysis), NMF (non-Negative Matrix Factorization) and receptor models were applied, and results showed that a particular indoor pollutant could normally be assigned to more than one source and among these sources finishing materials are important.[54] Building materials (e.g., wood floors) are the main source of dibutyl phthalate and xylenes.[42] Several studies highlight the importance of couches and upholstered chairs as sources of organophosphorus flame retardants (OPFR).[88,89]

7 | OCCUPANT DEMOGRAPHICS

Very few published articles have investigated the impact of occupant demographics on IAQ, apart from Sears et al.[90] who explored gender issues. However, there are studies[91,92] dedicated exclusively to a part of the population, and studies[93,94] where difference in exposure to different pollutants was investigated among different groups of the population (see Table S1).

According to previous studies, the elderly and children below 3 years are in general exposed more frequently to indoor pollutants, and consequently they have increased negative health effects (e.g., dermatitis, respiratory illness)[92,95–103] because they spend more time indoors. Moreover, recently it has been shown that in-utero exposure to indoor air pollution or tobacco smoke affects cognitive development.[104]

Most studies of babies and toddlers have focused on PM and VOCs, especially HCHO.[91,95,100,103,105] There are very few studies where SVOCs and specific compounds (e.g., phthalates) are investigated only for children.[91,93,94] High concentrations of several indoor pollutants (HCHO, VOCs, PM) have been linked as well with respiratory problems or impulse control problems and impaired cognitive control in older children.[79,90,92,106]

There are several measurements in elderly homes directed mainly at the health and comfort effects of IAQ in relation to ventilation, indoor air filtration, and elderly behaviors. Some works focused on particles,[107,108] a single study monitored only CO_2[101] and most studies include measurements of particles and gas phase pollutant concentrations (CO_2, TVOCs, O_3, HCHO, and CO).[96–99,102,109,110] Some of these studies demonstrated the important health effects (coronary, respiratory, skin, headaches, etc.) of several indoor pollutants and the importance of ventilation[96–99,101,102] and air filtration, especially for reducing levels of $PM_{2.5.}$[107] In general, poorer IAQ in nursing homes and elderly care homes was observed during winter rather than summer, normally assigned to reduced ventilation.[99,102]

To the authors' knowledge, there is only one study in the considered period which looked at gender differences and children.[90] This study that deals with dwellings close to coal-fired power plant highlighted the fact that the association between exposure to PM_{10} concentration and Behavior Assessment and Research System Continuous Performance Test commission errors among females were higher. Some papers studied only women[111–113] or women and children.[106,114] In these studies, the particularities of exposure among women, especially in low-income homes, due to spending long hours in poorly ventilated kitchen, using solid fuel for cooking, heating, etc. were considered.[111,112] Higher levels of some indoor pollutants such as CO, NO_2, H_2S, $PM_{2.5}$, and CO_2 were associated with health problems such as upper respiratory infection, dizziness, eye irritation, rhinitis, sneezing, persistent headache, and anemia in pregnancy.[106,114] Franklin et al.[113] investigated HCHO, NO_2 and VOC concentrations and birth data and only HCHO was associated with poorer birth outcomes (birth weight and head circumference).

From the authors' point of view this part of the impact of occupant demography on IAQ is closely related to occupant activity, as the type of activities carried out by occupants largely depends on age and gender. Moreover, body emissions can also be an important factor to consider in demography.[115,116]

8 | OCCUPANT ACTIVITIES

Theoretically, any human form of activity in residential buildings is a potential source of pollution, and therefore, will have an impact on IAQ (see Table S2). At-home activity can be treated as a variable emission source because it occurs with a different intensity depending on, for example, the age of the person, their scope of household activities, habits and frequency of activities, volume of the enclosed space, ventilation rate and number of occupants.

The most important pollutants released into the indoor air as a consequence of occupant activities (this is the focus of this review) and human emissions[115,116] are as follows: PM, CO, NO, SO_2, CO_2, NO_2, NH_3, VOCs, SVOCs, PAHs, chlorinated organic compounds and HCHO plus bacteria, fungi and viruses as biological contaminants. There are few available scientific studies on the impact of a specific type of at-home activity on IAQ; most are just case studies of monitoring measurements, or the result of wider national surveys.

Combustion (including smoking) is the greatest contributor to indoor air pollution of all at-home activities, and is the main indoor air source of PM, including ultrafine particles (UFPs) and BC, CO, PAHs, and oxides of nitrogen (NOx).[69,105,117–119] Conventional cigarette smoking and e-vaping are responsible for emissions of NO, CO, BTEX, acrolein, acrylamide, acetaldehyde, HCHO, and PMS. Additionally, e-cigarettes can be a source of Ni, Ag, and Cu particles.[120] Some studies have shown that candle burning can initiate particle formation and contribute to the PM concentration; burning scented candles and incense will generate VOCs, including HCHO and acrolein (see Table S1).

Fragranced consumer products (cleaning supplies, laundry detergents, fabric softeners, essentials oils, soaps, personal care products, colognes, hand sanitizers) are common VOC sources (terpenes, specifically limonene, α- and β-pinene) and by reactions with ozone they generate secondary pollutants. This is also a problem with air fresheners and deodorizers.[121] Electronic goods, furnishings, building, and textile materials are also important source of SVOC volatilization and accumulation in indoor dust, with the most studied being brominated flame retardants, polybrominated diphenyl ethers, hexabromocyclododecanes, OPFRs, short-chain chlorinated paraffins, and heavy metals.[30,122,123] Mechanical abrasion of household goods is another source of indoor pollutants, so cleaning activities, an important part of the daily household routine, can either improve or degrade IAQ.[124] Vacuuming can disperse particles from high emission rates with bagged vacuum cleaner to very low rates with HEPA filtered vacuum cleaners.[125] Cosmetics, health, and dry-cleaning products (impregnating agents, waxes), lubricants, conditioners can emit synthetic musks, polyfluorinated compounds, and phthalate esters. Moreover, siloxanes and parabens can be found in shampoos, body and facial creams, and deodorants.[126] Some pollutants released into the air during specific activities (cleaning, air freshening) may be subject to radical and oxidation reactions, which results in the formation of secondary air pollutants and particle nucleation (see Table S1). Humans and house animals are the main source of bioaerosols in indoor air. They are also responsible for the emission of CO_2, water vapor and some VOCs.[51,127,128] Due to the large variety of at-home activities, inclusion of these as parameters during IAQ measurements is complex, that is, which chemicals should be selected to represent the activities and what importance to assign to them in the final IAQ assessment. It is worth noting that these activities usually occur in a logical sequence, not simultaneously. For example, cleaning will be associated with vacuuming, which includes cleaning agents, disinfectants, and air fresheners, and often airing the rooms. However, these activities are performed each time with a different frequency and completion time.

9 | COOKING

Since cooking is a universal activity in dwellings and since it has been one of the most studies activities, a section for this activity has been included in this review. Studies related to the impact of cooking on IAQ are summarized in Table S3. The most studied pollutants are particles. Other pollutants emitted during cooking involve VOCs[129] including carbonyl compounds,[130] SVOCs (e.g., PAHs, fatty acids) and NOx.[131]

Cooking particles contain over 200 chemical components[132] including inorganic ions, metals and carbonaceous compounds, such as OC (PAHs, carbonyl compounds, fatty acids, dicarboxylic acids and n-alkanes) and BC.[133–136] The two most concerning cooking particles' components in terms of health risk are trace metallic elements[134] and PAHs.[112] PAHs are found both in the gas and particulate phases and include many carcinogenic and mutagenic compounds.[137]

Cooking emissions change with different factors, which include, but are not limited to the cooking oil used and the temperature of cooking,[138] the energy sources (gas burners and electric burners),[139,140] the condiments used,[141] the material being cooked, for example, meat,[142,143] the cooking pan or vessel used[144–146] and the ventilation strategies including the presence of an extraction hood.[131,147,148]

Cooking styles include, but are not limited to African, Asian, Western, and Middle Eastern. Cooking methods involve boiling, steaming, stewing, stir-frying, pan-frying, deep-frying, grilling, broiling, oven baking, toasting, and microwaving. Both cooking styles and cooking methods influence the emission of UFPs.[149–151] Many studies showed that an increase in the cooking oil temperature increases the particle number, mass concentration, and mode diameter.[136,152–154]

With respect to particle total number emission rates, the oils were ranked as olive > coconut > corn > soybean, canola > safflower > peanut. Olive, coconut, corn, and peanut oils generated higher total particle number than safflower, soybean, and canola oils at 197°C.[152,155,156]

Evidence from many studies has shown that cooking on a gas stove produces in general a higher level of UFPs, PM, and NOx than electric-stove cooking.[131,151,156,157]

Cooking appliance type is another factor in aerosol formation during the cooking process. Experiments showed that SVOCs and detergent residue adsorb onto the metal surfaces. After the stove was heated, these compounds desorbed and evaporated. They then produced particles when these evaporated gases cooled down to room temperature.[145,158] Successive heating of an empty pan on an electric stove was demonstrated to result in zero emissions.[144,145] Moreover, trace elements translocate from the cooking pan into the heated oil, and this affects the concentration of trace elements in the PM phase.[146]

All cooking styles use additives and condiments in their recipes, such as salt (sea salt and table salt) and black pepper. Research in this area suggests that condiments can influence PM and VOCs emissions during cooking. It was found that sea salt and table salt reduced emissions of $PM_{2.5}$ and total particle number from heated soybean and canola oils[141] and stir-fry spices could be an important source of terpenes.[129]

As has been commented before in this review, ventilation is of great significance in controlling indoor pollutants and it has been shown to be extremely important in cooking emissions. In general, NV is not adequate for controlling indoor air pollutants; extractions hoods are required.[131,147,148]

10 | CONCLUSIONS AND RESEARCH NEEDS

Based on this literature search, the following conclusions about the impact of different parameters on IAQ, methodological gaps, areas that require further research and recommendations can be formulated.

10.1 | Parameters that impact on IAQ

Indoor Air Quality is strongly influenced by the quality of *outdoor air* used as fresh air for *ventilation*. Both indoor and outdoor pollutant concentrations add together to provide the IAQ and in consequence, outdoor pollution must be measured to separate its impact on the total IAQ.

Natural ventilation depends on factors such as window opening status, type of windows, weather (temperature, rain, wind speed and direction), and locations of windows and doors. Filtration and system maintenance are important factors to be considered for MV system. It is crucial that natural and MV are characterized correctly in future measurement campaigns.

Building characteristics affect air circulation patterns and emissions. Most published studies relevant to the influence of *house location* on IAQ are focused on *surroundings*, *local direct emissions* and *seasonal* or *climate impact*. Sometimes contradictory conclusions can be found in literature, such as the effects of weather and seasons and the effect of opening windows on the levels of indoor pollutants. These opposing results can be caused by the location of primary sources of the pollutants and the location, use, type, or age of the building.

Finishing materials most affecting IAQ are floor and wall materials with larger off-gassing, covering larger areas, but the emission level depends on the pollutant considered. There is little quantitative data from previous studies about these in situ measurements of surface emissions—this topic needs to be tackled in future studies.

Renovation/retrofit is an important source of indoor pollutants to consider; however, in general off-gassing of VOCs normally decreases after some weeks/months after renovation is finished, although SVOC emissions could be important for longer periods. The impact of energy efficiency measures that were implemented during building and renovation on pollutant levels is not consistent in previous studies, possibly because studies have been done in different countries, with different building efficiency rules, or whether the building is a new build or retrofitted.

Research on the impact of ***occupant demography*** on IAQ for dwellings is scarce. This is unfortunate because IAQ is closely related to the type of activities carried out by occupants, which largely depends on age and gender. The type, frequency, and duration of ***activity*** performed by residents influence the state and dynamics of the IAQ. However, due to the large variety of these activities, it is very difficult to quantify them and their possible interactions. Moreover, the frequency and duration are highly variable from home to home.

The use of indoor biomass and other solid fuel ***combustion sources*** for cooking or heating should be avoided to maintain an acceptable level of PM concentrations and other indoor pollutants.

***Cooking*,** an important activity for dwellings, has been found to be one of the major sources of indoor sub-10 nm particles. It also produces particles with metal trace elements and a variety of gases including, but not limited to alkanes, sterols, hydrocarbons, dicarboxylic acids, fatty acids, lactones, polycyclic aromatic, alkanones, and NOx. Cooking can also produce secondary organic aerosols (SOA). Factors affecting cooking emissions (gas and particle) include, but are not limited to cooking temperature, cooking oil, type of meat and vegetables, type and position (on the stove) of pans, additives, sauces, source of energy and ventilation strategies, including presence of an extraction hood.

Despite the intensive research that has been previously summarized, there are methodological gaps that need to be addressed in future studies.

10.2 | Methodological gaps

10.2.1 | Carbon dioxide

Measurements of CO_2 as a tracer gas and measure of ventilation efficiency is scarce in most of the reviewed manuscripts regarding the impact of building location on IAQ. The lack of an indicator of ventilation efficiency is a methodological gap in this type of studies.

10.2.2 | SVOCs in particle and gas phases

When measuring SVOCs, it is necessary to measure these compounds in both the gas and particle phases. Both measurements must be added or analyzed both simultaneously to obtain the total concentration when assessing the residents' exposure.

10.2.3 | Individual VOCs measurements

Most studies have measured groups of compounds, for example, TVOCs, and there are few where individual compounds have been quantified. Measurements of individual compounds are required to be able to elucidate sources and health effects.

10.2.4 | Pollutants from household chemicals

The links between chemicals in household products and the chemicals detected in indoor air and dust particles need to be better established. To do this, it is necessary to carry out studies where both concentrations of chemicals in consumer products and measuring the gas and particle concentrations of these chemicals must be reported and analyzed. An interlaboratory study including indoor pollutants (gas and particle phases) and consumer products is necessary to harmonize sampling protocols and analytical methods, and to obtain reliable and harmonized data that could help to fill the gap that currently exists concerning SVOCs in consumer products and SVOCs in the indoor environment.[126]

10.2.5 | Real-time measurements

Further studies including fast time resolution measurements for as many indoor pollutants as possible (VOCs, SVOCs, etc.) are desirable to corroborate the observations of Huangfu et al.[81] who showed that the concentrations of the VOCs were not in steady state and that there is a diurnal cycle in their concentrations.

10.2.6 | Longer campaigns

Exposure to emissions resulting from daily home activities require both high time resolution measurements and averaging for very long times.[159] Further studies comparing results from long-term measurements and off-line techniques are required.

10.2.7 | Sampling protocol

A major difficulty in assessing the impact of residents' activity on IAQ is the lack of a standardized air sampling protocol that specifies the location of sampling points within each space. Without this protocol it is difficult, nearly impossible to compare data obtained by different studies. Three standards provide some information on sampling procedures for indoor air: ISO 16000-5 and ISO 16000-12.

10.2.8 | Building and finishing materials and other parameters that needs to be reported in studies

Some studies have clearly reported the materials of walls and/or floors, whereas other studies did not mention the finishing type, furniture material, cleaning agent, or household activities, which are very critical elements for analyzing IAQ. However, not only is the material important but the area of these materials (and the ratio of door volume to material area) as well since both emissions and sinks due to building materials depend on the surface area of them.[160,161] These parameters must be reported.

10.3 | Areas that require further research

10.3.1 | O_3 and other short lifetime pollutants (OH•, Cl•, etc.) and their implications for formation of secondary pollutants

There are few studies that measured indoor O_3, and especially other short lifetime oxidizing pollutants (e.g., OH•, Cl•, etc.), and their interactions with anthropogenic pollutants present indoors that can form secondary gaseous pollutants and SOA.

10.3.2 | Sub-10 nm particles

The emission rates, concentrations, and dynamics of sub-10 nm particles emitted during cooking are rarely investigated although their health impact is very important.[162] However, research directions should refocus to understand the emissions of the sub-10 nm and particularly, sub-3 nm particles during cooking activities as has been done in the recent paper published from HOMEChem campaign.[157]

10.3.3 | Particle composition

Few publications among those reviewed refer to chemical speciation of $PM_{2.5}$ and only one refers to UFP measurements. Most previous studies determined inorganic components[146,154,163,164] but very few included organics.[131,165] Reactive Oxygen Species concentration is important to determine the health impact of such particles.[163]

10.3.4 | Topography and presence of bodies of water

Topography and presence of bodies of water may be relevant to IAQ, because it could affect the ventilation rate when NV is used as it affects RH; however, to the authors' knowledge, there have been no studies focusing on the impacts of these two parameters on IAQ in dwellings.

10.3.5 | Floor plan and building maintenance

In the studied period, there were few published papers investigating the impact of building maintenance, glass surface area, floor ratio, the presence of a swimming pool/spa attached to the building, orientation or the presence of a restaurant on the ground floor of the building on IAQ. There are contradictory results about the impact of the number of floors[51,61] on the indoor pollutant concentrations. Moreover, there is little information on VOC concentrations in basements and their impact on the IAQ in the living area.[56]

10.3.6 | Room volume

Studies on the impact of room volume on the IAQ are also very sparse although it may have an important effect on indoor pollutants.[40,166]

10.3.7 | Other facilities on the ground floor

It has been shown that IAQ in apartments above facilities such as dry-cleaning shop or a nail salon are affected specially related to tetrachloroethylene concentrations.[167–169] However, these studies are quite old, and new studies where the current inhabitants' exposure to this pollutant and other chemicals[170] used in this kind of business are necessary.

10.3.8 | Residential ventilation

In the period investigated, few studies focused on the influence of bedroom air quality and ventilation on sleep quality.[171] Studies investigating the impact of interaction between ventilation and room volume on IAQ are also sparse. Few studies have been conducted to study the impact of ventilation system control on IAQ by monitoring the indoor environmental parameters and ventilation rate. Ventilation is a quantitative parameter when MV is used, but most residential buildings in Middle and North Europe use NV where procedures to quantify this ventilation method need to be understood in detail.

Most studies cited in ventilation section have monitored the pollutant concentrations in bedrooms, where inhabitants spend one-third of their lives.[171] However, it is surprising that standards normally have no recommendations for bedroom ventilation but only provide a suggested ventilation rate for the entire dwelling.[171] Significantly higher CO_2 concentrations in bedrooms were found in cold seasons than in temperate seasons, which indicates inefficient ventilation during sleep, which may negatively impact personal performance the following day. In consequence, more studies on the impact of IAQ in bedrooms when the inhabitants are sleeping are needed[171] in the future.

10.3.9 | Seasonal studies

Some contradictory conclusions were found on the impact of seasonal variation, types of heating systems and windows' opening status in relation with the effect of ventilation on IAQ.[10,17,46,54–56] It is important to resolve these conflicting conclusions.

10.3.10 | Sustainable buildings

Further studies comparing IAQ in green dwellings should be conducted in different countries with different green certifications, using similar monitoring and reporting methods for long periods, including several indoor pollutants, not just CO_2. As most of the reviewed studies were done in European countries, it is recommended to expand these studies to countries with different climates.[172] Moreover, green building materials that have improved or impaired IAQ in green residential buildings should be identified and their emissions investigated.

10.3.11 | Finishing materials as sinks and not only sources

There are many more studies about the emission of different pollutants from different types of materials used in dwellings than about their impact as sinks of indoor pollutants. Studies considering both aspects are required.

10.3.12 | Gender

Health effects[173] and indoor syndrome impact[174] are different for women and men. Consequently, more research is required exploring the impact of gender in relation to the activities, products used, human emissions, etc.

10.3.13 | Single activities

There are few studies devoted exclusively to assessing the impact of individual activities on IAQ, such as dishwasher cycle,[175] cleaning,[176,177] and vacuuming.[125] This type of research clearly does not reflect normal behavior because these activities are usually performed along with other activities. However, recent experiments in model houses have demonstrated their value as a source of valuable information for emissions of specific groups of pollutants from specific activities.[178–180]

10.3.14 | Spatial distribution of aerosols and SOA from cooking

Recently some studies have been published in relation to gases and the size distribution and composition of particles during cooking.[179,181,182] However, further studies considering the type of the buildings, surface materials, and ventilation rate of residential buildings are necessary. For such investigations, computational fluid dynamics and spatial monitoring of cooking aerosol in dwellings, using low-cost monitors would be necessary. Moreover, further studies are required to further understand SOA formation from cooking emissions and their health impact.

10.3.15 | Cooking style

While the literature characterized emissions from different cooking styles including Western and Asian styles, there is a substantial lack of studies addressing Middle Eastern, Mediterranean and African cooking styles, especially considering the effect of different types of dwellings.

10.3.16 | Cooking aerosol and health

While household solid fuel cooking has been identified as a major cause of premature death due to indoor activities, the use of solid fuels for cooking has globally decreased, particularly in developed countries.[183] Thus, research on cooking aerosols has switched to cleaner energy such as gas or electric-stove cooking. However, the health risks associated with such sources of energy exists, particularly in poorly ventilated homes and requires further exploration.[134,135,184,185] Some epidemiological studies demonstrated no associations between gas-stove cooking and respiratory symptoms, while other epidemiological studies did report associations between respiratory symptoms[186] and gas-stove cooking.[186–193]

A major existing gap in the cooking aerosol literature was identified to be the health effect of cooking aerosols, particularly chronic health effects. Acute health effects from cooking aerosols have been studied in the literature but with a significant gap on nervous health effects. Only two studies have addressed the impact of cooking aerosols on the human brain during gas stove and electric-stove cooking.[155,194]

10.4 | Recommended location/s to carry out measurements in dwellings

Ideally, it would be desirable to measure in all rooms, but when it is not possible, and the aim of the study is to determine the possible health impact on inhabitants it is recommended to carry out a questionnaire to determine the rooms where inhabitants spend most of their time.[95] In most of the reviewed studies, measurements

TABLE 2 Rooms relevant to study health impact of Indoor Air Quality for different population sectors

Population groups	Rooms–Where to measure?
Women from low-income backgrounds	Kitchens and living rooms
Elderly people living in nursery homes	Bedrooms and common zones (living room)
Teenagers and young children	Bedrooms
Babies	Bedrooms and living rooms
Working from home	Bedrooms, living rooms and offices

were conducted in bedrooms and living/dining rooms, and to a lesser extent, in kitchens and bathrooms. Table 2 summarizes the most relevant rooms to study the health impact for different population sectors.

However, the studied pollutant is also important when selecting which room to monitor, as can be seen in Table 1 and Table S1. To monitor PM, the kitchen is probably the most relevant room, while bedroom would be for monitoring HCHO. In any case, the three most frequently measured groups of pollutants in dwellings are $PM_{2.5}$, NO_2, and VOCs, followed by CO_2, HCHO, and O_3.

Concluding, future studies of residential IAQ must be more thorough and consistent with their reported parameters to allow analyses that can be verified and to provide trusted data that can be universally accepted by the IAQ community.

AUTHOR CONTRIBUTIONS

M.T. Baeza_Romero: conceptualization (lead), investigation (equal), project administration (equal), writing (equal), writing-review & editing (lead). M. R. Dudzinska: funding acquisition (lead), methodology (lead), investigation (equal), project administration (equal), writing (equal), writing-review & editing (equal). M. Amouei Torkmahalleh: investigation, writing. N. Barros: investigation (equal), writing (equal). A. M. Coggins: investigation (equal), project administration (equal), writing (equal). D. Gazioglu Ruzgar: investigation (equal), writing (equal). I. Kildsgaard: writing-review & editing (equal). M. Naseri: investigation (equal), writing (equal). L. Rong: investigation (equal), writing (equal). J. Saffell: writing-review & editing (equal). A.M. Scutaru: investigation (equal), writing (equal). A. Staszowska: investigation (equal), writing (equal), writing-review (equal).

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CONFLICT OF INTEREST

No conflict of interest declared.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

1. Holgate S, Stokes-Lampard H. Air pollution—a wicked problem. *BMJ*. 2017;357:j2814.
2. Allen JG, Macomber JD. *Healthy Buildings – How Indoor Spaces Drive Performance and Productivity*. Harvard University Press; 2020.
3. Klepeis NE, Nelson WC, Ott WR, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Anal Environ Epidemiol*. 2001;11(3):231-252.
4. Conrad A, Seiwert M, Hünken A, Quarcoo D, Schlaud M, Groneberg D. The German Environmental Survey for Children (GerES IV): reference values and distributions for time-location patterns of German children. *Int J Hyg Environ Health*. 2013;216(1):25-34.
5. Harrison RM, Hester RE. *Indoor Air Pollution*. The Royal Society of Chemistry; 2019.
6. Castro-Codesal ML, Dehaan K, Bedi PK, et al. Long-term benefits in sleep, breathing and growth and changes in adherence and complications in children using noninvasive ventilation. *Can J Respir Crit Care Sleep Med*. 2020;4(2):115-123.
7. Fan X, Shao H, Sakamoto M, et al. The effects of ventilation and temperature on sleep quality and next-day work performance: pilot measurements in a climate chamber. *Build Environ*. 2022;209:108666.
8. Strøm-Tejsen P, Zukowska D, Wargocki P, Wyon DP. The effects of bedroom air quality on sleep and next-day performance. *Indoor Air*. 2016;26(5):679-686.
9. Nations TU. *International Recommendations for Construction Statistics, Statistical papers, Series M, No. 47, Revision 1*. United Nation; 1997.

10. Mentese S, Tasdibi D. Assessment of residential exposure to volatile organic compounds (VOCs) and carbon dioxide (CO2). *Global NEST J*. 2017;19(4):7.
11. Jung CC, Hsu NY, Su HJ. Temporal and spatial variations in IAQ and its association with building characteristics and human activities in tropical and subtropical areas. *Build Environ*. 2019;163:106249.
12. Jeong C-H, Salehi S, Wu J, et al. Indoor measurements of air pollutants in residential houses in urban and suburban areas: indoor versus ambient concentrations. *Sci Total Environ*. 2019;693:133446.
13. Jung CR, Nishihama Y, Nakayama SF, et al. Indoor air quality of 5,000 households and its determinants. Part B: volatile organic compounds and inorganic gaseous pollutants in the Japan Environment and Children's study. *Environ Res*. 2021;197:111135.
14. Nishihama Y, Jung C-R, Nakayama SF, et al. Indoor air quality of 5,000 households and its determinants. Part A: particulate matter (PM2. 5 and PM10–2.5) concentrations in the Japan Environment and Children's Study. *Environ Res*. 2021;198:111196.
15. Singer BC, Chan WR, Kim YS, Offermann FJ, Walker IS. Indoor air quality in California homes with code required mechanical ventilation. *Indoor Air*. 2020;30(5):885-899.
16. Taylor J, Davies M, Mavrogianni A, et al. Mapping indoor overheating and air pollution risk modification across Great Britain: a modelling study. *Build Environ*. 2016;99:1-12.
17. Langer S, Ramalho O, Derbez M, Ribéron J, Kirchner S, Mandin C. Indoor environmental quality in French dwellings and building characteristics. *Atmos Environ*. 2016;128:82-91.
18. Bani Mfarrej MF, Qafisheh NA, Bahloul MM. Investigation of indoor air quality inside houses from UAE. *Air, Soil Water Res*. 2020;13:1178622120928912.
19. Khan MU, Li J, Zhang G, Malik RN. New insight into the levels, distribution and health risk diagnosis of indoor and outdoor dust-bound FRs in colder, rural and industrial zones of Pakistan. *Environ Pollut*. 2016;216:662-674.
20. Kotzias D. Built environment and indoor air quality: the case of volatile organic compounds. *AIMS Environ Sci*. 2021;8(2):13.
21. Liu C, Huang X, Li J. Outdoor benzene highly impacts indoor concentrations globally. *Sci Total Environ*. 2020;720:137640.
22. Liu C, Miao X, Li J. Outdoor formaldehyde matters and substantially impacts indoor formaldehyde concentrations. *Build Environ*. 2019;158:145-150.
23. Salthammer T. Data on formaldehyde sources, formaldehyde concentrations and air exchange rates in European housings. *Data Brief*. 2019;22:400-435.
24. Fadeyi MO. Ozone in indoor environments: research progress in the past 15 years. *Sustain Cities Soc*. 2015;18:78-94.
25. Nazaroff WW, Weschler CJ. Indoor ozone: concentrations and influencing factors. *Indoor Air*. 2022;32(1):e12942.
26. Barros N, Borrego C, Toll I, Soriano C, Jiménez P, Baldasano JM. Urban photochemical pollution in the Iberian Peninsula: Lisbon and Barcelona airsheds. *J Air Waste Manage Assoc*. 2003;53(3):347-359.
27. Shaw C, Boulic M, Longley I, Mitchell T, Pierse N, Howden-Chapman P. The association between indoor and outdoor NO2 levels: a case study in 50 residences in an urban neighbourhood in New Zealand. *Sustain Cities Soc*. 2020;56:102093.
28. Barros N, Carvalho M, Silva C, et al. Environmental and biological monitoring of benzene, toluene, ethylbenzene and xylene (BTEX) exposure in residents living near gas stations. *J Toxicol Environ Health A*. 2019;82(9):550-563.
29. Barros NA, Fontes T, Silva MP, Manso MC. How wide should be the adjacent area to an urban motorway to prevent potential health impacts from traffic emissions. *Transp Res Part A Policy Pract*. 2013;50:113-128.
30. Demirtepe H, Melymuk L, Diamond ML, et al. Linking past uses of legacy SVOCs with today's indoor levels and human exposure. *Environ Int*. 2019;127:653-663.
31. Ramacher MOP, Karl M, Bieser J, Jalkanen J-P, Johansson L. Urban population exposure to NO x emissions from local shipping in three Baltic Sea harbour cities–a generic approach. *Atmospheric Chem Phys*. 2019;19(14):9153-9179.
32. Shrestha PM, Humphrey JL, Carlton EJ, et al. Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons. *Int J Environ Res Public Health*. 2019;16(19):3535.
33. Zhou S, Young CJ, VandenBoer TC, Kahan TF. Role of location, season, occupant activity, and chemistry in indoor ozone and nitrogen oxide mixing ratios. *Environ Sci: Processes Impacts*. 2019;21(8):1374-1383.
34. Chang T, Ren D, Shen Z, et al. Indoor air pollution levels in decorated residences and public places over Xi'an, China. *Aerosol Air Qual Res*. 2017;17(9):2197-2205.
35. Coombs KC, Chew GL, Schaffer C, et al. Indoor air quality in green-renovated vs. non-green low-income homes of children living in a temperate region of US (Ohio). *Sci Total Environ*. 2016;554-555:178-185.
36. Du L, Leivo V, Prasauskas T, Täubel M, Martuzevicius D, Haverinen-Shaughnessy U. Effects of energy retrofits on indoor air quality in multifamily buildings. *Indoor Air*. 2019;29(4):686-697.
37. Broderick Á, Byrne M, Armstrong S, Sheahan J, Coggins AM. A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing. *Build Environ*. 2017;122:126-133.
38. Fisk WJ, Singer BC, Chan WR. Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: a review of empirical data. *Build Environ*. 2020;180:107067.
39. Frey SE, Destaillats H, Cohn S, Ahrentzen S, Fraser MP. The effects of an energy efficiency retrofit on indoor air quality. *Indoor Air*. 2015;25(2):210-219.
40. Yin X. Pollution pattern of formaldehyde and TVOC in indoor air and its control measures. *Nat Environ Pollut Technol*. 2017;16(2):579-585.
41. Vardoulakis S, Giagloglou E, Steinle S, et al. Indoor exposure to selected air pollutants in the home environment: a systematic review. *Int J Environ Res Public Health*. 2020;17(23):8972.
42. Dodson RE, Udesky JO, Colton MD, et al. Chemical exposures in recently renovated low-income housing: influence of building materials and occupant activities. *Environ Int*. 2017;109:114-127.
43. Ortiz M, Itard L, Bluyssen PM. Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: a literature review. *Energ Buildings*. 2020;221:110102.
44. Steinemann A. Volatile emissions from common consumer products. *Air Qual Atmos Health*. 2015;8(3):273-281.
45. Colton MD, MacNaughton P, Vallarino J, et al. Indoor air quality in green vs conventional multifamily low-income housing. *Environ Sci Technol*. 2014;48(14):7833-7841.
46. Derbez M, Berthineau B, Cochet V, et al. Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Build Environ*. 2014;72:173-187.
47. Brown T, Dassonville C, Derbez M, et al. Relationships between socioeconomic and lifestyle factors and indoor air quality in French dwellings. *Environ Res*. 2015;140:385-396.
48. Sha B, Dahlberg A-K, Wiberg K, Ahrens L. Fluorotelomer alcohols (FTOHs), brominated flame retardants (BFRs), organophosphorus flame retardants (OPFRs) and cyclic volatile methylsiloxanes (cVMSs) in indoor air from occupational and home environments. *Environ Pollut*. 2018;241:319-330.
49. Wang X, Banks APW, He C, et al. Polycyclic aromatic hydrocarbons, polychlorinated biphenyls and legacy and current pesticides in indoor environment in Australia–occurrence, sources and exposure risks. *Sci Total Environ*. 2019;693:133588.

50. Shrestha PM, Humphrey JL, Barton KE, et al. Impact of low-income home energy-efficiency retrofits on building air tightness and healthy home indicators. *Sustainability*. 2019;11(9):2667.
51. Mečiarová Ľ, Vilčeková S, Burdová EK, Kiselák J. Factors effecting the total volatile organic compound (TVOC) concentrations in Slovak households. *Int J Environ Res Public Health*. 2017;14(12):1443.
52. Mallach G, St-Jean M, Macneill M, et al. Exhaust ventilation in attached garages improves residential indoor air quality. *Indoor Air*. 2016;27:487-499.
53. Hansen HH. *Guidelines for Ventilation Requirements in Buildings*. Publications Office of the European Union; 1992.
54. Rösch C, Kohajda T, Röder S, Bergen MV, Schlink U. Relationship between sources and patterns of VOCs in indoor air. *Atmos Pollut Res*. 2014;5(1):129-137.
55. Hou J, Zhang Y, Sun Y, et al. Air change rates at night in northeast Chinese homes. *Build Environ*. 2018;132:273-281.
56. Du L, Batterman S, Godwin C, Rowe Z, Chin JY. Air exchange rates and migration of VOCs in basements and residences. *Indoor Air*. 2015;25(6):598-609.
57. Liu J, Dai X, Li X, et al. Indoor air quality and occupants' ventilation habits in China: seasonal measurement and long-term monitoring. *Build Environ*. 2018;142:119-129.
58. Bekö G, Lund T, Nors F, Toftum J, Clausen G. Ventilation rates in the bedrooms of 500 Danish children. *Build Environ*. 2010;45(10):2289-2295.
59. Fan G, Xie J, Yoshino H, et al. Indoor environmental conditions in urban and rural homes with older people during heating season: a case in cold region, China. *Energ Buildings*. 2018;167:334-346.
60. Militello-Hourigan RE, Miller SL. The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes. *Build Environ*. 2018;144:573-582.
61. Ścibor M, Balcerzak B, Galbarczyk A, Targosz N, Jasienska G. Are we safe inside? Indoor air quality in relation to outdoor concentration of PM10 and PM2.5 and to characteristics of homes. *Sustain Cities Soc*. 2019;48:101537.
62. Stasiulaitiene I, Krugly E, Prasauskas T, et al. Infiltration of outdoor combustion-generated pollutants to indoors due to various ventilation regimes: a case of a single-family energy efficient building. *Build Environ*. 2019;157:235-241.
63. van Holsteijn IRCA, Li IWL, Valk IHJJ, Kornaat IW. Improving the energy and IAQ performance of ventilation systems in Dutch dwellings. *Int J Vent*. 2016;14(4):363-370.
64. Parajuli I, Lee H, Shrestha KR. Indoor air quality and ventilation assessment of rural mountainous households of Nepal. *Int J Sustain Built Environ*. 2016;5(2):301-311.
65. Yang S, Perret V, Hager Jörin C, Niculita-Hirzel H, Goyette Pernot J, Licina D. Volatile organic compounds in 169 energy-efficient dwellings in Switzerland. *Indoor Air*. 2020;30(3):481-491.
66. Lajoie P, Aubin D, Gingras V, et al. The IVAIRE project--a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. *Indoor Air*. 2015;25(6):582-597.
67. Canha N, Alves AC, Marta CS, et al. Compliance of indoor air quality during sleep with legislation and guidelines – a case study of Lisbon dwellings. *Environ Pollut*. 2020;264:114619.
68. Siponen T, Yli-Tuomi T, Tiittanen P, et al. Wood stove use and other determinants of personal and indoor exposures to particulate air pollution and ozone among elderly persons in a Northern Suburb. *Indoor Air*. 2019;29(3):413-422.
69. Vilčeková S, Apostoloski IZ, Mečiarová Ľ, Burdová EK, Kiseľák J. Investigation of indoor air quality in houses of Macedonia. *Int J Environ Res Public Health*. 2017;14(1):37.
70. Wheeler AJ, Gibson MD, MacNeill M, et al. Impacts of air cleaners on indoor air quality in residences impacted by wood smoke. *Environ Sci Tech*. 2014;48(20):12157-12163.
71. Barn P, Gombojav E, Ochir C, et al. The effect of portable HEPA filter air cleaners on indoor PM2.5 concentrations and second hand tobacco smoke exposure among pregnant women in Ulaanbaatar, Mongolia: the UGAAR randomized controlled trial. *Sci Total Environ*. 2018;615:1379-1389.
72. Fang L, Norris C, Johnson K, et al. Toxic volatile organic compounds in 20 homes in Shanghai: concentrations, inhalation health risks, and the impacts of household air cleaning. *Build Environ*. 2019;157:309-318.
73. Pei J, Ji L. Secondary VOCs emission from used fibrous filters in portable air cleaners and ventilation systems. *Build Environ*. 2018;142:464-471.
74. Luengas A, Barona A, Hort C, Gallastegui G, Platel V, Elias A. A review of indoor air treatment technologies. *Rev Environ Sci Biotechnol*. 2015;14(3):499-522.
75. Xiao R, Mo J, Zhang Y, Gao D. An in-situ thermally regenerated air purifier for indoor formaldehyde removal. *Indoor Air*. 2018;28(2):266-275.
76. Aldred JR, Darling E, Morrison G, Siegel J, Corsi RL. Benefit-cost analysis of commercially available activated carbon filters for indoor ozone removal in single-family homes. *Indoor Air*. 2016;26(3):501-512.
77. Isiugo K, Jandarov R, Cox J, et al. Predicting indoor concentrations of black carbon in residential environments. *Atmos Environ*. 2019;201:223-230.
78. Cai J, Yu W, Li B, et al. Particle removal efficiency of a household portable air cleaner in real-world residences: a single-blind crossover field study. *Energ Buildings*. 2019;203:109464.
79. Singleton R, Salkoski AJ, Bulkow L, et al. Housing characteristics and indoor air quality in households of Alaska Native children with chronic lung conditions. *Indoor Air*. 2017;27(2):478-486.
80. Hernandez G, Wallis SL, Graves I, Narain S, Birchmore R, Berry T-A. The effect of ventilation on volatile organic compounds produced by new furnishings in residential buildings. *Atmos Environ*. 2020;6:100069.
81. Huangfu Y, Lima NM, O'Keeffe PT, et al. Diel variation of formaldehyde levels and other VOCs in homes driven by temperature dependent infiltration and emission rates. *Build Environ*. 2019;159:106153.
82. Huang L, Qian H, Deng S, et al. Urban residential indoor volatile organic compounds in summer, Beijing: profile, concentration and source characterization. *Atmos Environ*. 2018;188:1-11.
83. Huang Y, Su T, Wang L, et al. Evaluation and characterization of volatile air toxics indoors in a heavy polluted city of northwestern China in wintertime. *Sci Total Environ*. 2019;662:470-480.
84. Kim UJ, Wang Y, Li W, Kannan K. Occurrence of and human exposure to organophosphate flame retardants/plasticizers in indoor air and dust from various microenvironments in the United States. *Environ Int*. 2019;125:342-349.
85. Hammel SC, Levasseur JL, Hoffman K, et al. Children's exposure to phthalates and non-phthalate plasticizers in the home: the TESIE study. *Environ Int*. 2019;132:105061.
86. Rodgers KM, Bennett D, Moran R, et al. Do flame retardant concentrations change in dust after older upholstered furniture is replaced? *Environ Int*. 2021;153:106513.
87. Zhou L, Püttmann W. Distributions of organophosphate flame retardants (OPFRs) in three dust size fractions from homes and building material markets. *Environ Pollut*. 2019;245:343-352.
88. Sakhi AK, Cequier E, Becher R, et al. Concentrations of selected chemicals in indoor air from Norwegian homes and schools. *Sci Total Environ*. 2019;674:1-8.
89. Hammel SC, Hoffman K, Lorenzo AM, et al. Associations between flame retardant applications in furniture foam, house dust levels, and residents' serum levels. *Environ Int*. 2017;107:181-189.
90. Sears CG, Sears L, Zierold KM. Sex differences in the association between exposure to indoor particulate matter and cognitive

control among children (age 6–14 years) living near coal-fired power plants. *Neurotoxicol Teratol*. 2020;78:106855.
91. Dallongeville A, Costet N, Zmirou-Navier D, et al. Volatile and semi-volatile organic compounds of respiratory health relevance in French dwellings. *Indoor Air*. 2016;26(3):426-438.
92. Dannemiller KC, Murphy JS, Dixon SL, et al. Formaldehyde concentrations in household air of asthma patients determined using colorimetric detector tubes. *Indoor Air*. 2013;23(4):285-294.
93. Luongo G, Östman C. Organophosphate and phthalate esters in settled dust from apartment buildings in Stockholm. *Indoor Air*. 2016;26(3):414-425.
94. Wang D, Wang P, Zhu Y, et al. Seasonal variation and human exposure assessment of legacy and novel brominated flame retardants in PM2. 5 in different microenvironments in Beijing, China. *Ecotoxicol Environ Saf*. 2019;173:526-534.
95. Pickett AR, Bell ML. Assessment of indoor air pollution in homes with infants. *Int J Environ Res Public Health*. 2011;8(12):4502-4520.
96. Mendes A, Pereira C, Mendes D, et al. Indoor air quality and thermal comfort-results of a pilot study in elderly care centers in Portugal. *J Toxicol Environ Health A*. 2013;76(4–5):333-344.
97. Almeida-Silva M, Wolterbeek HT, Almeida SM. Elderly exposure to indoor air pollutants. *Atmos Environ*. 2014;85:54-63.
98. Bentayeb M, Norback D, Bednarek M, et al. Indoor air quality, ventilation and respiratory health in elderly residents living in nursing homes in Europe. *Eur Respir J*. 2015;45(5):1228-1238.
99. Tunsaringkarn T, Prueksasit T, Morknoy D, et al. Indoor air assessment, health risks, and their relationship among elderly residents in urban warrens of Bangkok, Thailand. *Air Qual Atmos Health*. 2015;8(6):603-615.
100. Huang C, Wang X, Liu W, et al. Household indoor air quality and its associations with childhood asthma in Shanghai, China: on-site inspected methods and preliminary results. *Environ Res*. 2016;151:154-167.
101. Serrano-Jiménez A, Lizana J, Molina-Huelva M, Barrios-Padura Á. Indoor environmental quality in social housing with elderly occupants in Spain: measurement results and retrofit opportunities. *J Build Eng*. 2020;30:101264.
102. Pereira EL, Madacussengua O, Baptista P, Feliciano M. Assessment of indoor air quality in geriatric environments of southwestern Europe. *Aerobiologia*. 2021;37(1):139-153.
103. Kwon JH, Kim E, Chang MH, et al. Indoor total volatile organic compounds exposure at 6 months followed by atopic dermatitis at 3 years in children. *Pediatr Allergy Immunol*. 2015;26(4):352-358.
104. Christensen GM, Rowcliffe C, Chen J, et al. In-utero exposure to indoor air pollution or tobacco smoke and cognitive development in a South African birth cohort study. *Sci Total Environ*. 2022;834:155394.
105. Stamatelopoulou A, Asimakopoulos DN, Maggos T. Effects of PM, TVOCs and comfort parameters on indoor air quality of residences with young children. *Build Environ*. 2019;150:233-244.
106. Rumchev K, Zhao Y, Spickett J. Health risk assessment of indoor air quality, socioeconomic and house characteristics on respiratory health among women and children of Tirupur, South India. *Int J Environ Res Public Health*. 2017;14(4):429.
107. Karottki DG, Spilak M, Frederiksen M, et al. An indoor air filtration study in homes of elderly: cardiovascular and respiratory effects of exposure to particulate matter. *Environ Health*. 2013;12:116.
108. Buczyńska AJ, Krata A, Van Grieken R, et al. Composition of PM2.5 and PM1 on high and low pollution event days and its relation to indoor air quality in a home for the elderly. *Sci Total Environ*. 2014;490:134-143.
109. Mendes A, Bonassi S, Aguiar L, et al. Indoor air quality and thermal comfort in elderly care centers. *Urban Clim*. 2015;14:486-501.
110. Tong X, Wang B, Dai W-T, et al. Indoor air pollutant exposure and determinant factors controlling household air quality for elderly people in Hong Kong. *Air Qual Atmos Health*. 2018;11(6):695-704.
111. Singh AL, Jamal S. Assessing vulnerability of women to indoor air pollution. *Res J Environ Earth Sci*. 2012;4(11):982-989.
112. Mu L, Liu L, Niu R, et al. Indoor air pollution and risk of lung cancer among Chinese female non-smokers. *Cancer Causes Control*. 2013;24(3):439-450.
113. Franklin P, Tan M, Hemy N, Hall GL. Maternal exposure to indoor air pollution and birth outcomes. *Int J Environ Res Public Health*. 2019;16(8):1364.
114. Oguntoke O, Adebulehin AT, Annegarn HJ. Biomass energy utilisation, air quality and the health of rural women and children in Ido LGA, south-western Nigeria. *Indoor Built Environ*. 2013;22(3):528-534.
115. Tang X, Misztal PK, Nazaroff WW, Goldstein AH. Volatile organic compound emissions from humans indoors. *Environ Sci Technol*. 2016;50(23):12686-12694.
116. Morrison GC, Eftekhari A, Majluf F, Krechmer JE. Yields and variability of ozone reaction products from human skin. *Environ Sci Technol*. 2020;55(1):179-187.
117. Downward GS, Hu W, Rothman N, et al. Outdoor, indoor, and personal black carbon exposure from cookstoves burning solid fuels. *Indoor Air*. 2016;26(5):784-795.
118. Ni K, Carter E, Schauer JJ, et al. Seasonal variation in outdoor, indoor, and personal air pollution exposures of women using wood stoves in the Tibetan Plateau: baseline assessment for an energy intervention study. *Environ Int*. 2016;94:449-457.
119. Langer S, Ramalho O, Le Ponner E, Derbez M, Kirchner S, Mandin C. Perceived indoor air quality and its relationship to air pollutants in French dwellings. *Indoor Air*. 2017;27(6):1168-1176.
120. Marques P, Piqueras L, Sanz M-J. An updated overview of e-cigarette impact on human health. *Respir Res*. 2021;22(1):151.
121. Steinemann A. Ten questions concerning fragrance-free policies and indoor environments. *Build Environ*. 2019;159:106054.
122. Gümperlein I, Fischer E, Dietrich-Gümperlein G, et al. Acute health effects of desktop 3D printing (fused deposition modeling) using acrylonitrile butadiene styrene and polylactic acid materials: an experimental exposure study in human volunteers. *Indoor Air*. 2018;28(4):611-623.
123. Reche C, Viana M, Querol X, Corcellas C, Barceló D, Eljarrat E. Particle-phase concentrations and sources of legacy and novel flame retardants in outdoor and indoor environments across Spain. *Sci Total Environ*. 2019;649:1541-1552.
124. Melymuk L, Bohlin-Nizzetto P, Kukučka P, et al. Seasonality and indoor/outdoor relationships of flame retardants and PCBs in residential air. *Environ Pollut*. 2016;218:392-401.
125. Vicente ED, Vicente AM, Evtyugina M, et al. Impact of vacuum cleaning on indoor air quality. *Build Environ*. 2020;180:107059.
126. Lucattini L, Poma G, Covaci A, de Boer J, Lamoree MH, Leonards PEG. A review of semi-volatile organic compounds (SVOCs) in the indoor environment: occurrence in consumer products, indoor air and dust. *Chemosphere*. 2018;201:466-482.
127. Canha N, Lage J, Coutinho JT, Alves C, Almeida SM. Comparison of indoor air quality during sleep in smokers and non-smokers' bedrooms: a preliminary study. *Environ Pollut*. 2019;249:248-256.
128. Canha N, Teixeira C, Figueira M, Correia C. How is indoor air quality during sleep? A review of field studies. *Atmos*. 2021;12(1):110.
129. Liu T, Liu Q, Li Z, et al. Emission of volatile organic compounds and production of secondary organic aerosol from stir-frying spices. *Sci Total Environ*. 2017;599–600:1614-1621.
130. Xiang Z, Wang H, Stevanovic S, et al. Assessing impacts of factors on carbonyl compounds emissions produced from several typical Chinese cooking. *Build Environ*. 2017;125:348-355.
131. Zhao Y, Zhao B. Emissions of air pollutants from Chinese cooking: a literature review. Paper presented at: Building Simulation; 2018.

132. Zhao Y, Liu L, Tao P, et al. Review of effluents and health effects of cooking and the performance of kitchen ventilation. *Aerosol Air Qual Res*. 2019;19(8):1937-1959.
133. Abdullahi KL, Delgado-Saborit JM, Harrison RM. Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: a review. *Atmos Environ*. 2013;71:260-294.
134. Gorjinezhad S, Kerimray A, Amouei Torkmahalleh M, Keleş M, Ozturk F, Hopke PK. Quantifying trace elements in the emitted particulate matter during cooking and health risk assessment. *Environ Sci Pollut Res Int*. 2017;24(10):9515-9529.
135. Wang L, Zheng X, Stevanovic S, et al. Characterization particulate matter from several Chinese cooking dishes and implications in health effects. *J Environ Sci*. 2018;72:98-106.
136. Zhang Q, Gangupomu RH, Ramirez D, Zhu Y. Measurement of ultrafine particles and other air pollutants emitted by cooking activities. *Int J Environ Res Public Health*. 2010;7(4):1744-1759.
137. Bekö G, Weschler CJ, Wierzbicka A, et al. Ultrafine particles: exposure and source apportionment in 56 Danish homes. *Environ Sci Tech*. 2013;47(18):10240-10248.
138. Torkmahalleh MA, Goldasteh I, Zhao Y, et al. PM2.5 and ultrafine particles emitted during heating of commercial cooking oils. *Indoor Air*. 2012;22(6):483-491.
139. Wallace LA, Emmerich SJ, Howard-Reed C. Source strengths of ultrafine and fine particles due to cooking with a gas stove. *Environ Sci Tech*. 2004;38(8):2304-2311.
140. Wallace L, Wang F, Howard-Reed C, Persily A. Contribution of gas and electric stoves to residential ultrafine particle concentrations between 2 and 64 nm: size distributions and emission and coagulation rates. *Environ Sci Tech*. 2008;42(23):8641-8647.
141. Amouei Torkmahalleh M, Zhao Y, Hopke PK, Rossner A, Ferro AR. Additive impacts on particle emissions from heating low emitting cooking oils. *Atmos Environ*. 2013;74:194-198.
142. Torkmahalleh MA, Gorjinezhad S, Keles M, et al. A controlled study for the characterization of PM2.5 emitted during grilling ground beef meat. *J Aerosol Sci*. 2017;103:132-140.
143. Torkmahalleh MA, Kaibaldiyeva U, Kadyrbayeva A. A new computer model for the simulation of particulate matter formation from heated cooking oils using Aspen Plus. *Build Simul*. 2017;10(4):535-550.
144. Amouei Torkmahalleh M, Ospanova S, Baibatyrova A, Nurbay S, Zhanakhmet G, Shah D. Contributions of burner, pan, meat and salt to PM emission during grilling. *Environ Res*. 2018;164:11-17.
145. Wallace LA, Ott WR, Weschler CJ. Ultrafine particles from electric appliances and cooking pans: experiments suggesting desorption/nucleation of sorbed organics as the primary source. *Indoor Air*. 2015;25(5):536-546.
146. Broomandi P, Amouei Torkmahalleh M, Akturk M, et al. A new exposure route to trace elements in indoor particulate matter. *Indoor Air*. 2020;30(3):492-499.
147. Dobbin NA, Sun L, Wallace L, et al. The benefit of kitchen exhaust fan use after cooking – an experimental assessment. *Build Environ*. 2018;135:286-296.
148. Sun L, Wallace LA. Residential cooking and use of kitchen ventilation: the impact on exposure. *J Air Waste Manage Assoc*. 2021;71(7):830-843.
149. Chen C, Zhao Y, Zhao B. Emission rates of multiple air pollutants generated from chinese residential cooking. *Environ Sci Tech*. 2018;52(3):1081-1087.
150. See SW, Balasubramanian R. Chemical characteristics of fine particles emitted from different gas cooking methods. *Atmos Environ*. 2008;42(39):8852-8862.
151. Dennekamp M, Howarth S, Dick CA, Cherrie JW, Donaldson K, Seaton A. Ultrafine particles and nitrogen oxides generated by gas and electric cooking. *Occup Environ Med*. 2001;58(8):511-516.
152. Gao J, Cao C, Zhang X, Luo Z. Volume-based size distribution of accumulation and coarse particles (PM0.1–10) from cooking fume during oil heating. *Build Environ*. 2013;59:575-580.
153. Siegmann K, Sattler K. Aerosol from hot cooking oil, a possible health hazard. *J Aerosol Sci*. 1996;27:S493-S494.
154. Torkmahalleh MA, Gorjinezhad S, Unluevcek HS, Hopke PK. Review of factors impacting emission/concentration of cooking generated particulate matter. *Sci Total Environ*. 2017;586:1046-1056.
155. Torkmahalleh MA, Naseri M, Nurzhan S, et al. Human exposure to aerosol from indoor gas stove cooking and the resulting nervous system responses. *Indoor Air*. 2022;32(2):e12983.
156. Buonanno G, Morawska L, Stabile L. Particle emission factors during cooking activities. *Atmos Environ*. 2009;43(20):3235-3242.
157. Patel S, Sankhyan S, Boedicker EK, et al. Indoor particulate matter during HOMEChem: concentrations, size distributions, and exposures. *Environ Sci Tech*. 2020;54(12):7107-7116.
158. Wallace LA, Ott WR, Weschler CJ, Lai ACK. Desorption of SVOCs from heated surfaces in the form of ultrafine particles. *Environ Sci Tech*. 2017;51(3):1140-1146.
159. Lunderberg DM, Misztal PK, Liu Y, et al. High-resolution exposure assessment for volatile organic compounds in two California residences. *Environ Sci Tech*. 2021;55(10):6740-6751.
160. Wagner A. *Floor Coverings and IAQ. Indoor Air Quality Update*. Mass, Cutter Information Corp; 1991.
161. Gonzalo FA, Griffin M, Laskosky J, Yost P, González-Lezcano RA. Assessment of indoor air quality in residential buildings of New England through actual data. *Sustainability*. 2022;14(2):739.
162. Pedata P, Malorni L, Sannolo N, et al. Characterization and inflammatory potential of sub-10nm particles from gas cooking appliances. *Chem Eng Trans*. 2016;47:433-438.
163. Dan EU, Ebong GA. Impact of cooking utensils on trace metal levels of processed food items. *Ann Food Sci Technol*. 2013;14(2):350-355.
164. Torkmahalleh MA, Sharifi H, Dareini M, Buonanno G. The impact of cooking pan material on ultrafine particle emission rates. 37th AAAR conference; October 14–18, 2019; Portland Oregon.
165. Jørgensen RB, Strandberg B, Sjaastad AK, Johansen A, Svendsen K. Simulated restaurant cook exposure to emissions of PAHs, mutagenic aldehydes, and particles from frying bacon. *J Occup Environ Hyg*. 2013;10(3):122-131.
166. de Gennaro G, Dambruoso PR, Di Gilio A, Di Palma V, Marzocca A, Tutino M. Discontinuous and continuous indoor air quality monitoring in homes with fireplaces or wood stoves as heating system. *Int J Environ Res Public Health*. 2015;13(1):78.
167. Garentano G, Gochfeld M. Factors affecting tetrachloroethylene concentrations in residence above dry cleaning establishment. *Arch Environ Health*. 2000;55:59-68.
168. Chiappini L, Delery L, Leoz-Garziandia E, Brouard B, Fagault Y. A first French assessment of population exposure to tetrachloroethylene from small dry cleaning facilities. *Indoor Air*. 2009;19(3):226-233.
169. Schreiber JS, Hudnell HK, Geller AM, et al. Apartment residents' and day care workers' exposures to tetrachloroethylene and deficits in visual contrast sensitivity. *Environ Health Perspect*. 2002;110(7):655-664.
170. Ceballos DM, Fellows KM, Evans AE, Janulewicz PA, Lee EG, Whittaker SG. Perchloroethylene and dry cleaning: it's time to move the industry to safer alternatives. *Front Public Health*. 2021;9:638082.
171. Sekhar C, Akimoto M, Fan X, et al. Bedroom ventilation: review of existing evidence and current standards. *Build Environ*. 2020;184:107229.
172. Moreno-Rangel A, Sharpe T, McGill G, Musau F. Indoor air quality in Passivhaus dwellings: a literature review. *International Journal of Environmental Research and Public Health*. 2020;17(13):4749.
173. Matsubara E, Kawai S. Gender differences in the psychophysiological effects induced by VOCs emitted from Japanese cedar (*Cryptomeria japonica*). *Environ Health Prev Med*. 2018;23(1):10.

174. Stenberg B, Wall S. Why do women report 'sick building symptoms' more often than men? *Soc Sci Med*. 1995;40(4):491-502.
175. Rovelli S, Cattaneo A, Fazio A, et al. VOCs measurements in residential buildings: quantification via thermal desorption and assessment of indoor concentrations in a case-study. *Atmos*. 2019;10(2):57.
176. Zhou S, Liu Z, Wang Z, et al. Hydrogen peroxide emission and fate indoors during non-bleach cleaning: a chamber and modeling study. *Environ Sci Tech*. 2020;54(24):15643-15651.
177. Wong JPS, Carslaw N, Zhao R, Zhou S, Abbatt JPD. Observations and impacts of bleach washing on indoor chlorine chemistry. *Indoor Air*. 2017;27(6):1082-1090.
178. Wang C, Bottorff B, Reidy E, et al. Cooking, bleach cleaning, and air conditioning strongly impact levels of HONO in a house. *Environ Sci Technol*. 2020;54(21):13488-13497.
179. Sankhyan S, Patel S, Katz EF, et al. Indoor black carbon and brown carbon concentrations from cooking and outdoor penetration: insights from the HOMEChem study. *Environ Sci: Processes Impacts*. 2021;23(10):1476-1487.
180. Katz EF, Lunderberg DM, Brown WL, et al. Large emissions of low-volatility siloxanes during residential oven use. *Environ Sci Technol Lett*. 2021;8(7):519-524.
181. Brown WL, Day DA, Stark H, et al. Real-time organic aerosol chemical speciation in the indoor environment using extractive electrospray ionization mass spectrometry. *Indoor Air*. 2021;31(1):141-155.
182. Katz EF, Guo H, Campuzano-Jost P, et al. Quantification of cooking organic aerosol in the indoor environment using aerodyne aerosol mass spectrometers. *Aerosol Sci Tech*. 2021;55(10):1099-1114.
183. Bonjour S, Adair-Rohani H, Wolf J, et al. Solid fuel use for household cooking: country and regional estimates for 1980-2010. *Environ Health Perspect*. 2013;121(7):784-790.
184. Zhang N, Han B, He F, et al. Chemical characteristic of PM2. 5 emission and inhalational carcinogenic risk of domestic Chinese cooking. *Environ Pollut*. 2017;227:24-30.
185. Sze-To GN, Wu CL, Chao CYH, Wan MP, Chan TC. Exposure and cancer risk toward cooking-generated ultrafine and coarse particles in Hong Kong homes. *HVAC&R Res*. 2012;18(1–2):204-216.
186. Jarvis D, Chinn S, Sterne J, Luczynska C, Burney P. The association of respiratory symptoms and lung function with the use of gas for cooking. European Community Respiratory Health Survey. *Eur Respir J*. 1998;11(3):651-658.
187. Corbo GM, Forastiere F, Agabiti N, et al. Effect of gas cooking on lung function in adolescents: modifying role of sex and immunoglobulin E. *Thorax*. 2001;56(7):536-540.
188. Eisner MD, Blanc PD. Gas stove use and respiratory health among adults with asthma in NHANES III. *Occup Environ Med*. 2003;60(10):759-764.
189. Hecht SS, Seow A, Wang M, et al. Elevated levels of volatile organic carcinogen and toxicant biomarkers in Chinese women who regularly cook at home. *Cancer Epidemiol Biomarkers Prev*. 2010;19(5):1185-1192.
190. Kumar R, Nagar JK, Raj N, et al. Impact of domestic air pollution from cooking fuel on respiratory allergies in children in India. *Asian Pac J Allergy Immunol*. 2008;26(4):213-222.
191. Moshammer H, Fletcher T, Heinrich J, et al. Gas cooking is associated with small reductions in lung function in children. *Eur Respir J*. 2010;36(2):249-254.
192. Wong GWK, Ko FWS, Hui DSC, et al. Factors associated with difference in prevalence of asthma in children from three cities in China: multicentre epidemiological survey. *BMJ*. 2004;329(7464):486.
193. Buonanno G, Marks GB, Morawska L. Health effects of daily airborne particle dose in children: direct association between personal dose and respiratory health effects. *Environ Pollut*. 2013;180:246-250.
194. Naseri M, Jouzizadeh M, Tabesh M, et al. The impact of frying aerosol on human brain activity. *Neurotoxicology*. 2019;74:149-161.
195. Doll SC, Davison EL, Painting BR. Weatherization impacts and baseline indoor environmental quality in low income single-family homes. *Build Environ*. 2016;107:181-190.
196. Francisco PW, Jacobs DE, Targos L, et al. Ventilation, indoor air quality, and health in homes undergoing weatherization. *Indoor Air*. 2017;27(2):463-477.
197. Doyi INY, Isley CF, Soltani NS, Taylor MP. Human exposure and risk associated with trace element concentrations in indoor dust from Australian homes. *Environ Int*. 2019;133:105125.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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