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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 16 000 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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SUPPORTING INFORMATION

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

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