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Review

Sources, levels, and determinants of indoor air pollutants in Europe: A systematic review

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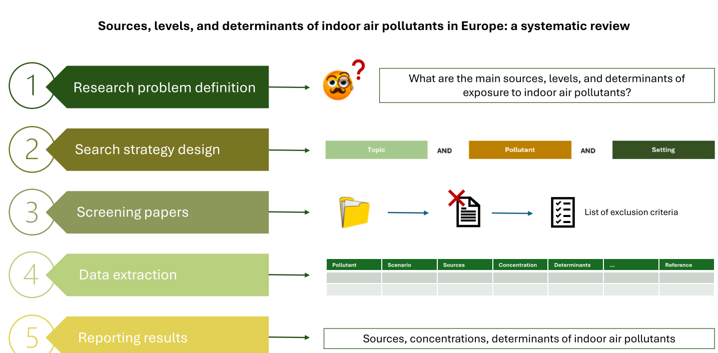
HIGHLIGHTS

- Sources and determinants of indoor air quality in Europe were reviewed.
- Sources identified were occupancy, human activity, cleaning products.
- Determinants identified were ventilation, type of building and number of occupants.
- This review supports the development of new policies and standards.

GRAPHICAL ABSTRACT



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A B S T R A C T

Clean air is a requirement for life, and the quality of indoor air is a health determinant since people spend most of their daily time indoors. The aim of this study was to systematically review the available evidence regarding the sources, determinants and concentrations of indoor air pollutants in a set of scenarios under study in K-HEALTHinAIR project. To this end, a systematic review was performed to review the available studies published between the years 2013–2023, for several settings (schools, homes, hospitals, lecture halls, retirement homes, public transports and canteens), conducted in Europe, where sources and determinants of the indoor pollutants concentrations was assessed. After a two-stage screening in abstract and full-text, 148 papers were included for data extraction. For particulate matter, carbon dioxide and volatile organic compounds, several emission sources were identified (occupancy, human activities, resuspension, cleaning products, disinfectants, craft activities, cooking, smoking), with ventilation, number of occupants, building characteristics, being considered as important determinants. This review made also possible to discuss some of the actions that are already in place or should be implemented in the future to prevent and control the presence of pollutants indoors.

1. Introduction

In high income countries, people spend 80 to 90 % of their time in indoor settings performing activities of daily living, working, and sleeping, where the presence of pollutants is a concern (Carslaw et al., 2024). Nevertheless, indoor air quality (IAQ) remains relatively understudied, leading to a lack of standards and to regulatory gaps (Morawska et al., 2024). Even so, Europe is the world region with more legislation and guidelines available, compared the other world regions, with 21 countries having legislation or guidelines for IAQ (Toyinbo et al., 2022). Particularly, the country members of the European Union had made an effort to fill the gaps in the area of IAQ in research and policy domains (European Commission, 2024). Recently, seven projects were funded under the Horizon Europe programme (K-HEALTHinAIR, SynAir-G, LEARN, TwinAIR, InChildHealth, INQUIRE, EDIAQI) aiming to understand the impacts on our health and well-being of those environmental, occupational and socio-economic risk factors that have the most significant or widespread societal impacts (IDEAL Cluster, 2023).

At international level, the Scientific and Technical Committee 34 (STC34) of the International Society of Indoor Air Quality and Climate (ISIAQ) made available an open access database where available guidelines and regulations of indoor air quality can be consulted (https://www.ieqguidelines.org/), thus overcoming constraints related with documentation only available in native languages and facilitating the access of policy makers, scientists, and practitioners (Toyinbo et al., 2022).

In the meantime, knowing the pollution sources (responsible for the pollutant presence indoors) and the key determinants (influence the pollutant level indoors) is extremely relevant to define the best risk management approaches at the technical and policy levels (Chojer et al., 2024). Several elements contribute to poor indoor air quality (IAQ) and pollutants can have their origin on the outdoor pollution, as well as sources that are unique to the indoor environment such as human occupancy and activities (e.g., smoking, burning solid fuels, cooking, and cleaning), and the building and its characteristics (structure, ventilation system, construction materials, insulation) (EPHA, 2024; WHO, 2010). Additionally, environmental factors such as temperature and humidity influence are mediators of indoor air quality (EPHA, 2024).

The aim of this study was to systematically review the available evidence regarding the sources and determinants of concentrations of indoor air pollutants, in settings (schools, homes, lecture halls, hospitals, retirement homes, public transports and canteens) being studied in the K-HEALTHinAIR project (www.k-healthinair.eu).

2. Methods

The literature review was performed based on the PRISMA Methodology (Shamseer et al., 2015), about sources and determinants of indoor air pollutants presence and concentrations (particulate matter, volatile organic compounds, nitrogen oxides, carbon dioxide, ozone, radon) in the European countries for the period 2013–2023. The search string considered three main groups: the topic, the pollutants, and the settings (Fig. S1).

The search was performed on 7 June 2023, and the search string used was: ((“indoor air” OR “indoor air pollution” OR “indoor air quality”) AND (“VOC” OR “particulate matter” OR “formaldehyde” OR “carbon dioxide” OR “nitrogen oxides” OR “ozone” OR “radon”) AND (“hospital” OR “public transport” OR “market” OR “canteen” OR “residence” OR “lecture hall” OR “home” OR “school”). Three peer-reviewed literature databases were searched: (i) Pubmed (all-fields and relevant MeSH terms); (ii) Scopus (only title-abstract-keywords: excludes conference papers, notes, editorials, and letters, etc.) and (iii) Web of Science (core collection only; excludes proceeding papers, meeting abstracts, news items, editorial material, and letters).

The inclusion criteria were: i) English language; ii) study reporting primary data; iii) timeframe 2013–2023; iv) studies developed in European countries. Grey literature sources were not considered. The references were collected, managed, deduplicated, and screened using Mendeley and Microsoft Excel software. Proceeding papers, meeting abstracts, news items, editorial material, and letters were excluded.

2.1. First stage screening

Relevance screening of the publications identified in the literature search was performed. The titles and abstracts were screened by two independent reviewers per reference with a third reviewer to resolve conflicts. References were excluded when two reviewers agreed on the exclusion. For the first stage, four questions were used sequentially to screen and select papers for further stages, summarized in the decision tree (Fig. 1): (Q1) Does it report primary data? (yes or maybe – include; no – exclude); (Q2) Does it report data for indoor air pollution? (yes or maybe – include; no – exclude); (Q3) Does it concern any of the following settings: hospital, retirement homes, metro station, market, canteens, student residence, lecture hall, homes, schools (primary and secondary schools)? (yes or maybe – include; no – exclude); (Q4) Was the study developed in a European country? (yes or maybe – include; no – exclude). References that fulfilled the inclusion criteria proceeded to full text screening, i.e., the second stage of screening.

2.2. Second stage screening

In the second stage, each complete paper (i.e., full-text) was examined by one reviewer, based on four questions, summarized in the decision tree (Fig. 1): Q4: Was the study developed in a European country? (yes – include; no – exclude); Q5: Is it an experimental study? (no – include; yes – exclude); Q6: Does it report levels of pollutants? (yes – include; no – exclude); Q7: Does it identify sources or determinants of exposure? (yes – include; no – exclude). Question Q4 was repeated since only studies developed in Europe were considered for this systematic review and this information frequently is not available in title and abstract.

2.3. Data extraction and analysis of sources and determinants of exposure

At a final stage, data were extracted considering several aspects of each paper related with setting characteristics, study design, pollutants, exceedance of available national legislation and/or guidelines as reported in each study, sources and determinants identified as such. Data regarding indoor air pollutants other than those considered in the search string was also extracted to have a more comprehensive review. A narrative synthesis of the review findings was generated qualitatively comparing the results of all studies for sources and determinants, organized by each setting and pollutant.

3. Results

3.1. Overview of the studies

The literature search yielded a total of 4370 papers among the three databases used (Scopus, Web of Science, and Pubmed), with a total of 1478 records examined at stage I and 703 records screened at stage II. Fig. 2 shows an overview of the papers obtained at each stage and the exclusion workflow.

In stage II, 555 papers were excluded due to several reasons: studies developed outside Europe (n = 335); studies developed under experimental and/or laboratorial conditions (n = 119); and for not reporting levels of indoor pollutants and not identifying sources or determinants as such (n = 101). Therefore, 148 papers were eligible for data extraction and analysis. Fig. 3 describes the number of settings studied in screened papers. Schools were the most studied (n = 73, 45 %), followed by homes (n = 59, 37 %). The least explored settings were the lecture halls (n = 9, 6 %), hospitals (n = 8, 5 %), retirement homes (n = 5, 3 %), transportation (n = 5, 3 %) and canteens (n = 1, 1 %).

Overall, the selected studies presented different study designs, with cross-sectional studies being the most frequently reported (n = 129), followed by cohort studies (n = 9) and case-control studies (n = 10). Regarding analysis of results, 27/73 studies in schools, 27/59 studies in homes, and 3/8 studies in hospitals, performed a statistical analysis to establish an association between sources and pollutants and to identify the determinants of indoor concentrations. Statistical methods for source and determinant attribution ranged from inferential tests such as Mann-Whitney, Kruskal-Wallis, ANOVA, to more complex analysis using Principal Component Analysis, linear mixed effects and multivariate regression models.

3.2. Schools

Eligible studies for data extraction focused on primary and secondary schools, thus revealing the potential exposure of children from 6 to 18 years, teachers, and other support staff. Sources and determinants of indoor air pollutants are described in the Table 1.

For carbon dioxide (CO_2), most of the studies identified occupancy as the main source, with the number of people being a determinant factor for indoor CO_2 levels (Cabovská et al., 2022; Chatzidiakou et al., 2014; Hänninen et al., 2017; Kaewrat et al., 2021; Lazovic et al., 2016;

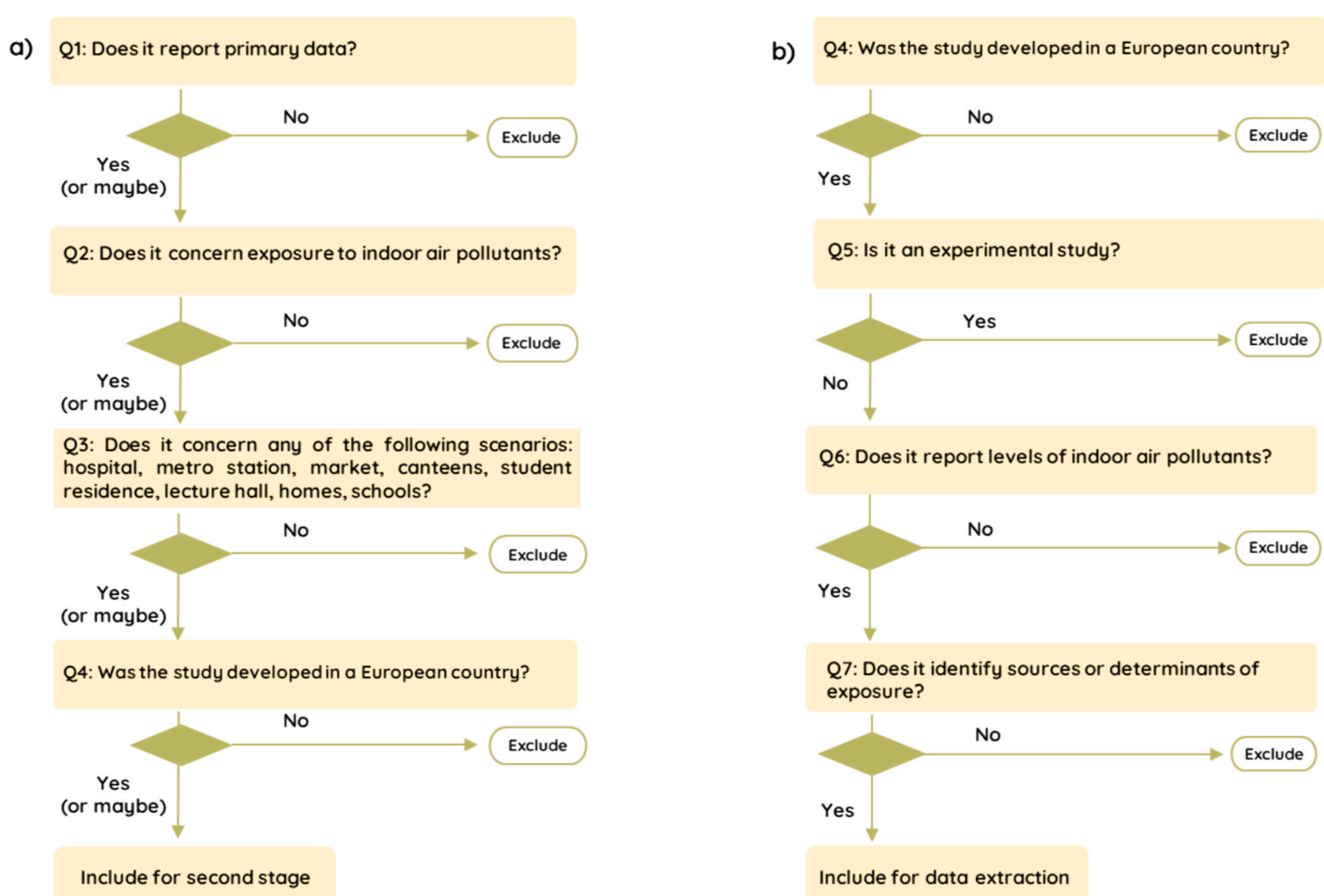

Fig. 1. Decision tree for stage I screening (a) and stage II screening (b).

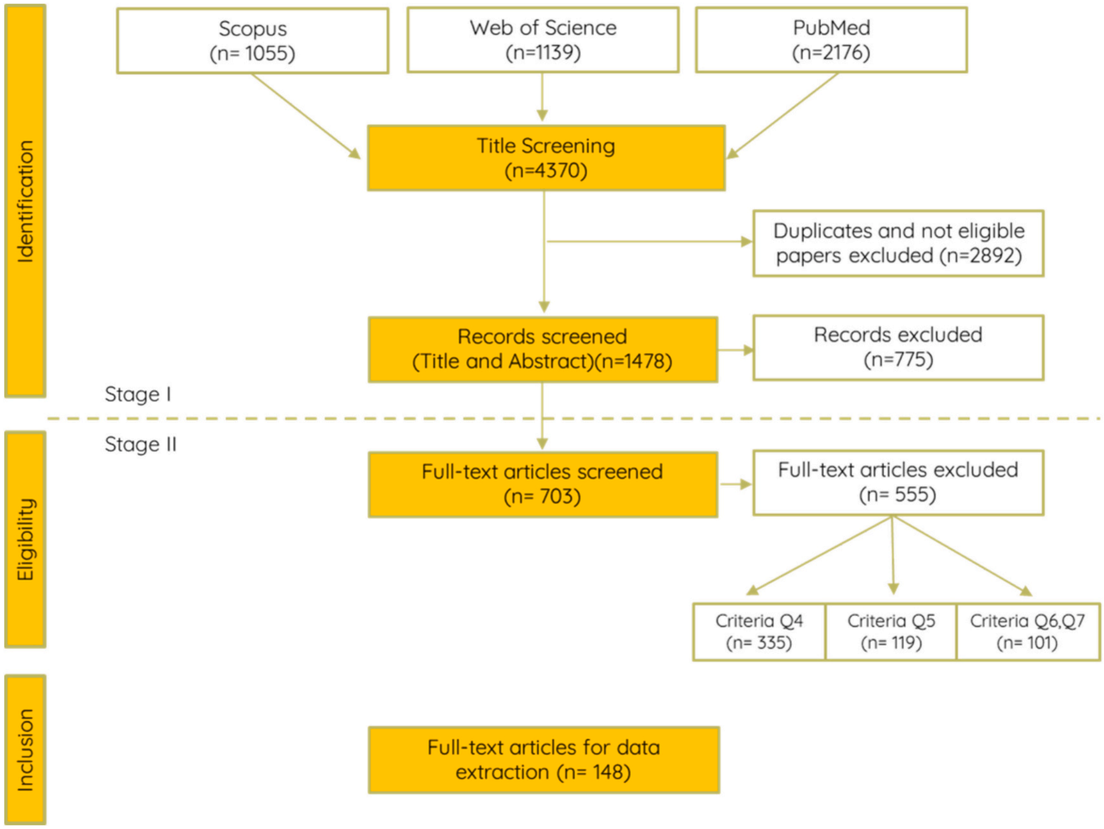

Fig. 2. Workflow and results for stage I and stage II of the systematic literature review.

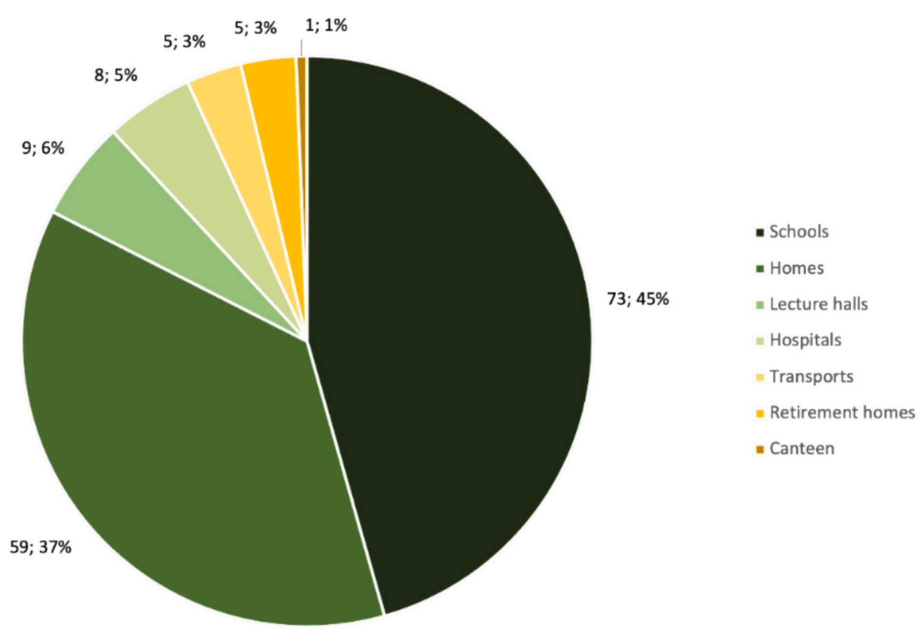

Fig. 3. Settings studied in the scientific literature eligible for data extraction.

Madureira et al., 2016; Madureira et al., 2016c; Muhič and Muhič, 2022; Sá et al., 2017; Schibuola and Tambani, 2020; Stabile et al., 2016; Turanjanin et al., 2014; Ukëhaxhaj et al., 2023; Vornanen-Winqvist et al., 2018a, 2018b). (Lazovic et al., 2016) Regarding determinants of the presence of indoor pollutants, the type of ventilation (Jovanović et al., 2014; Kovacevic et al., 2015; Lazovic et al., 2016; Madureira et al., 2016; Mečiarová et al., 2018; Sá et al., 2017; Turanjanin et al., 2014; Villanueva et al., 2021; Vornanen-Winqvist et al., 2018a), classroom volume (Madureira et al., 2016; Madureira et al., 2016c), building maintenance (Stabile et al., 2016), classroom orientation (Turanjanin et al., 2014), or physical activities (Lazovic et al., 2016), were also considered important factors with influence on indoors CO_2 levels.

The most recent analytical techniques have made it possible to quantify different Volatile Organic Compounds (VOCs). Nevertheless,

Table 1
Sources, concentrations, and determinants of indoor air pollutants presence in schools.

Indoor air pollutant	Sources of exposure	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants of exposure	References
CO_2	Occupancy Outdoor air	410–3780 ppm	1000–4434 ppm	Yes 13/21 studies	Number of occupants Type of ventilation (natural, mechanical) Room volume Season Building maintenance Classroom orientation Physical activities	(Alves et al., 2016; Cabovská et al., 2022; Chatzidiakou et al., 2014; Hänninen et al., 2017; Jovanović et al., 2014; Lazovic et al., 2016; Madureira et al., 2016; Madureira et al., 2016; Mečiarová et al., 2018; Muhič and Muhič, 2022; Rufo et al., 2016; Sá et al., 2017; Schibuola and Tambani, 2020; Stabile et al., 2016; Turanjanin et al., 2014; Ukëhaxhaj et al., 2023; Villanueva et al., 2021; Vornanen-Winqvist et al., 2018a; Vornanen-Winqvist et al., 2018b)
Total VOC	Cleaning products Floor material Class materials (art & crafts, textiles) Consumer products	19–1543 μg/m^3	84–820.2 μg/m^3	Not reported 2/8 studies No exceedance 6/8 studies	Number of occupants Type of ventilation (natural, mechanical) Season Room volume Type of floor	(Alves et al., 2016; Ferreira and Cardoso, 2014; Jovanović et al., 2014; Madureira et al., 2016; Madureira et al., 2016c; Mečiarová et al., 2018; Ninyà et al., 2022; Sá et al., 2017)
Benzene	Outdoor environment Floor material Class materials (textiles)	0.44–5.24 μg/m^3	0.6–20.1 μg/m^3	Not reported	Type of ventilation (natural, mechanical) Classroom orientation	(Brdarić et al., 2019; de Gennaro et al., 2013; Fromme et al., 2013; Madureira et al., 2016; Marzocca et al., 2017; Szabados et al., 2021; Ukëhaxhaj et al., 2023)
Limonene	Cleaning products Whiteboard Class activities Class materials (textiles)	3.08–26.6 μg/m^3	3.6–249 μg/m^3	Not available	Type of ventilation (natural, mechanical)	(de Gennaro et al., 2013; Fromme et al., 2013; Marzocca et al., 2017; Stamp et al., 2020; Szabados et al., 2021; Villanueva et al., 2018)
Pinene	Cleaning products Class materials (textiles) Class activities	4.85–55.6 μg/m^3	9.9–73 μg/m^3	Not available	Type of ventilation (natural, mechanical)	(de Gennaro et al., 2013; Fromme et al., 2013; Stamp et al., 2020; Szabados et al., 2021)
Toluene	Outdoor environment Class materials (art & crafts, textiles)	1.5–25 μg/m^3	1.9–202.5 μg/m^3	Not available	Type of ventilation (natural, mechanical)	(Fromme et al., 2013; Madureira et al., 2016; Marzocca et al., 2017; Szabados et al., 2021)
Naphtalene Tetrachloroethylene Tricholoroethylene	Class materials (textiles)	0.5–2.18 μg/m^3 0.09–4.4 μg/m^3 0.19–0.45 μg/m^3	1–6.05 μg/m^3 0.6–67.1 μg/m^3 NR	Not available	Type of ventilation (natural, mechanical)	(Fromme et al., 2013)
Ethylbenzene Styrene Xylenes	Outdoor environment Class materials (art & crafts) Cleaning products	0.76–1.64 μg/m^3 0.44–1.75 μg/m^3 5.37 μg/m^3	1.4–9.14 μg/m^3 0.43–4.2 μg/m^3 34.6 μg/m^3	Not available	No determinants identified	(Marzocca et al., 2017; Szabados et al., 2021)
Acetaldehyde Hexanal Propionaldehyde	No sources identified	5.28–9.31 μg/m^3 9.17–15.8 μg/m^3 1.49 μg/m^3	11 μg/m^3 26.9–32.7 μg/m^3 6.54 μg/m^3	Not available	No determinants identified	(Szabados et al., 2021)
Decane	Furniture	NR	5.86 μg/m^3	Not available	No determinants identified	(de Gennaro et al., 2013)
2-butoxyethanol	Cleaning products	31.5 μg/m^3	46.4 μg/m^3	Not available	No determinants identified	(Marzocca et al., 2017)
Formaldehyde	Furniture (wood-based) Organic sources (dampness, mold) Electronics Class activities Smoking Traffic Class materials (textiles)	0.01–102 μg/m^3	12.9–126.9 μg/m^3	Yes 1/7 studies	Type of ventilation (natural, mechanical) Building' characteristics (location, age) Type of floor	(Brdarić et al., 2019; Cabovská et al., 2022; Hu et al., 2022; Jovanović et al., 2014; Sá et al., 2017; Szabados et al., 2021; Ukëhaxhaj et al., 2023)
NO_2	Outdoor environment Traffic Wall material Heating/combustion	4.89–31 μg/m^3	13.7–69 μg/m^3	Not available	Type of ventilation (natural, mechanical) Classroom orientation Number of occupants Floor level	(Cabovská et al., 2022; Chatzidiakou et al., 2015; Hu et al., 2022; Szabados et al., 2021; Ukëhaxhaj et al., 2023; Villanueva et al., 2018)

(*continued on next page*)

Table 1 (*continued*)

Indoor air pollutant	Sources of exposure	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants of exposure	References
					Building' characteristics (location, age)	
$PM_{0.1}$	Outdoor environment Traffic Resuspension Chalk Cooking Wood	2445–19,241 part/cm^3	3985–185,000 part/cm^3	Not reported	Type of ventilation (natural, mechanical) Number of occupants Building' characteristics (location) Type of board Floor level Type of floor Building with kitchen Room volume Time (period of day)	(Cavaleiro Rufo et al., 2016; Paunescu et al., 2017; Reche et al., 2014; Rivas et al., 2014; Klara Slezakova et al., 2019; Villanueva et al., 2021)
$PM_{1.0}$	Chalk Traffic Occupancy Outdoor environment	2.4–70.1 μg/m^3	Not reported	Not reported	Building location Ventilation Number of occupants	(Pacitto et al., 2018; Polednik, 2013; Sá et al., 2017)
$PM_{2.5}$	Occupancy Chalk Outdoor air Resuspension (cleaning activities and movements of students) Traffic Soil Construction material Class materials (art & crafts, textiles) Organic sources (dampness, mold)	1.27–117 μg/m^3	27.1–279 μg/m^3	Yes 6/18 studies	Number of occupants Type of ventilation (natural, mechanical) Classroom orientation Building' characteristics (location) Type of playground Season Construction material Floor level Windows' material	(Alves et al., 2016; Amato et al., 2014; Cabovská et al., 2022; Chatzidiakou et al., 2015; Di Gilio et al., 2017; Faria et al., 2020; Ferreira and Cardoso, 2014; Jovanović et al., 2014; Kovacevic et al., 2015; Pacitto et al., 2018; Polednik, 2013; Rivas et al., 2015, 2014; Sá et al., 2017; Stamp et al., 2020; Tofful and Perrino, 2015; Villanueva et al., 2021; Vornanen-Winqvist et al., 2018a)
PM_{10}	Occupancy Chalk Resuspension (cleaning activities and movements of students) Outdoor air Soil Organic sources (dampness, mold) Construction material Craft activities Traffic	14–388 μg/m^3	20–490 μg/m^3	Yes 7/21 studies	Number of occupants Type of ventilation (natural, mechanical) Classroom orientation Building' characteristics (location) Class activities Floor level Season Footwear (shoes/socks)	(Almeida et al., 2016; Alves et al., 2016; Barmparesos et al., 2020; Cabovská et al., 2022; Chatzidiakou et al., 2014; Faria et al., 2020; Ferreira and Cardoso, 2014; Fischer et al., 2015; Fromme et al., 2013; Jovanović et al., 2014; Kovacevic et al., 2015; Leppänen et al., 2020; Madureira et al., 2016; Madureira et al., 2016c; Pacitto et al., 2018; Pallarés et al., 2021; Polednik, 2013; Sá et al., 2017; Schibuola and Tambani, 2020; Szabados et al., 2021; Villanueva et al., 2021)
CO	Outdoor environment Smoking Combustion	0.42–9.1 ppm 0.48–905 μg/m^3	121.8 ppm 1700 μg/m^3	Yes 2/4	Ventilation Season	(Alves et al., 2016; Ferreira and Cardoso, 2014; Hänninen et al., 2017; Sá et al., 2017)
Radon	Geogenic (outdoor environment) Soil Mining	29–381 Bq/m^3	109–952.8 Bq/m^3	Yes 3/6	Floor level Ventilation Number of occupants Building' characteristics (age, construction material) Room location Room Volume Floor type	(Azara et al., 2018; Branco et al., 2016; Curado et al., 2020; Ćurguz et al., 2015; Gulan et al., 2023; Madureira et al., 2016b)
O_3	Outdoor environment Copy machine	0.002–0.08 ppm 4.8–37 μg/m^3	3 ppm 15.9–31.4 μg/m^3	Not reported	Type of ventilation (natural, mechanical) Season	(Cabovská et al., 2022; Jovanović et al., 2014; Sá et al., 2017)

CO_2 = Carbon dioxide; VOC=Volatile Organic Compounds; PM = Particulate Matter; CO=Carbon Monoxide; NO_2 = Nitrogen Dioxide; O_3 = Ozone total VOCs are still the most frequently used parameter in indoor air quality studies. The most relevant sources identified for the presence of VOCs' in schools are cleaning products and materials used for students' activities (e.g., crafts, paints, glues) (Madureira et al., 2016; Mečiarová et al., 2018; Nicole Ninyà et al., 2022; Sá et al., 2017). Furniture, floors, and textiles were also recognized as possible sources of VOCs (Madureira et al., 2016; Madureira et al., 2016c). Contribution from outdoor sources were also identified for benzene (de Gennaro et al., 2013; Madureira et al., 2016; Marzocca et al., 2017; Szabados et al., 2021; Ukëhaxhaj et al., 2023), toluene, ethylbenzene and xylenes (Marzocca et al., 2017; Szabados et al., 2021), and styrene (Marzocca et al., 2017). The importance of good planning and installation of mechanical ventilation systems must be stressed to avoid the transport of pollutants from outdoor or other indoor locations. These systems should have a periodic maintenance plan to prevent them from becoming a potential source of exposure. Several factors were identified as determinants of indoor VOCs levels, with ventilation conditions being one of the most frequent (Jovanović et al., 2014; Madureira et al., 2016; Mečiarová et al., 2018). The number of occupants (Madureira et al., 2016c), type of floor materials (Madureira et al., 2016), or location in the building (Ukëhaxhaj et al., 2023) were also recognized as determinants. There were some VOCs quantified in schools for which it was not possible to identify the main sources (hexanal, propionaldehyde, acetaldehyde) highlighting the need for further research dedicated to understanding the presence of these compounds indoors.

Formaldehyde is considered a VOC of particular concern, due to its common presence in indoor environments, its high levels and toxicity (Jiang et al., 2018). From the studies analysed the main sources of formaldehyde identified in schools were furniture and wood-based materials (Brdarić et al., 2019; Jovanović et al., 2014; Sá et al., 2017), textiles (Jovanović et al., 2014), electronic equipment (Brdarić et al., 2019), smoking (Hu et al., 2022), and presence of molds/moisture (Brdarić et al., 2019). Following the same pattern of other VOCs, ventilation conditions and type of ventilation (e.g., natural or mechanical) were determinants of indoor formaldehyde levels (Brdarić et al., 2019; Cabovská et al., 2022; Hu et al., 2022; Jovanović et al., 2014; Sá et al., 2017), as well as building characteristics (e.g., type of floor, location, and year of construction) (Jovanović et al., 2014; Ukëhaxhaj et al., 2023).

Although some indoor sources such as wall materials and heating systems by combustion were identified for nitrogen dioxide (NO_2), the outdoor sources are the major contributors (i.e., outdoor air and traffic) and identified in more articles as such (Cabovská et al., 2022; Chatzidiakou et al., 2015; Hu et al., 2022; Szabados et al., 2021; Ukëhaxhaj et al., 2023; Villanueva et al., 2018). Regarding the factors that may influence the indoor levels, the type of ventilation (Brdarić et al., 2019; Cabovská et al., 2022; Jovanović et al., 2014), the number of occupants (Villanueva et al., 2018), and aspects related to building characteristics (e.g., year of construction, location, floor level) (Chatzidiakou et al., 2014; Ukëhaxhaj et al., 2023) were identified as determinants of the presence of NO_2 in schools.

Most studies assessed the presence of 10 μm and 2.5 μm particulate matter (PM_{10} and $PM_{2.5}$, respectively), although three studies quantified 1.0 μm particles (Pacitto et al., 2018; Polednik, 2013; Sá et al., 2017) and seven studies quantified 0.1 μm particles (ultrafine particles) (Cavaleiro Rufo et al., 2016; Paunescu et al., 2017; Reche et al., 2014; Rivas et al., 2014; Slezakova et al., 2019; Villanueva et al., 2021). The outdoor environment, mainly air pollution (schools located in heavy traffic areas), was identified as contributing factor to indoor levels of PM_{10} (Almeida et al., 2016; Alves et al., 2016; Kovacevic et al., 2015; Pacitto et al., 2018; Pallarés et al., 2021; Polednik, 2013; Villanueva et al., 2021), $PM_{2.5}$ (Alves et al., 2016; Amato et al., 2014; Kovacevic et al., 2015; Polednik, 2013; Szabados et al., 2021; Villanueva et al., 2021), $PM_{1.0}$ (Pacitto et al., 2018) and $PM_{0.1}$ (Cavaleiro Rufo et al., 2016; Reche et al., 2014; Slezakova et al., 2019; Villanueva et al., 2021). The presence of students in school classrooms was also a source of contamination, just as the number of people was noted as a determinant (Almeida et al., 2016; Alves et al., 2016; Barmparesos et al., 2020; Cabovská et al., 2022; Carballo et al., 2021; Di Gilio et al., 2017; Faria et al., 2020; Fischer et al., 2015; Jovanović et al., 2014; Kovacevic et al., 2015; Połednik, 2013; Schibuola and Tambani, 2020). This is also related to times of students' activities, movements inside the classrooms and cleaning at the end of the day, which several studies highlighted to contribute to increase indoor levels of particulate matter. A very characteristic aspect of school settings is the use of chalk, and this was noted in several studies as a source of indoor particulate matter (PM_{10}, $PM_{2.5}$, $PM_{1.0}$ and $PM_{0.1}$) (Amato et al., 2014; Faria et al., 2020; Pacitto et al., 2018; Połednik, 2013; Rivas et al., 2014; Sá et al., 2017; Slezakova et al., 2019). Following the pattern of other indoor pollutants, ventilation plays a significant role in the indoor particles levels, being identified as a determinant for all particles size (Alves et al., 2016; Barmparesos et al., 2020; Cabovská et al., 2022; Carballo et al., 2021; Chatzidiakou et al., 2014; Fischer et al., 2015; Jovanović et al., 2014; Kovacevic et al., 2015; Madureira et al., 2016c; Polednik, 2013; Reche et al., 2014; Slezakova et al., 2019; Stamp et al., 2020; Tofful and Perrino, 2015; Villanueva et al., 2021; Vornanen-Winqvist et al., 2018a). Several aspects related to the building characteristics were also identified as potential determinants: the floor level (Cavaleiro Rufo et al., 2016; Slezakova et al., 2022), the construction materials (walls, windows) (Połednik, 2013; Tofful and Perrino, 2015), type of playground (Amato et al., 2014), or room orientation (influenced also by outdoor air pollution levels) (Amato et al., 2014; Reche et al., 2014). An important contribution was the study that assessed the differences in indoor particulate matter levels between schools where students wear socks and schools where students kept their shoes inside (Leppänen et al., 2020). This study showed that there is a significant difference in indoor PM_{10} levels and that schools where students wear socks presented lower levels of PM_{10}. This information is relevant for the development of future mitigation measures.

Few studies quantified the presence of carbon monoxide (CO) in school facilities; nevertheless, several sources were identified such as combustion systems for heating (Hänninen et al., 2017), smoking (in secondary school) (Alves et al., 2016), and outdoor sources (Sá et al., 2017). Ventilation and season were identified as the main determinants of the presence of CO in schools (Ferreira and Cardoso, 2014; Sá et al., 2017).

The geological origin of radon is well known and described in literature, and therefore, the main sources described in schools were related to outdoor sources (e.g., soil and nearby mining activities, granitic formations in the soil) (Azara et al., 2018; Branco et al., 2016; Curado et al., 2020; Gulan et al., 2023; Madureira et al., 2016b). Since it is difficult to eliminate the sources, it is essential to invest in reducing indoor contamination by defining adequate characteristics for buildings, particularly for schools. Ventilation (Branco et al., 2016; Curado et al., 2020; Gulan et al., 2023), construction materials (Azara et al., 2018; Curguz et al., 2020), room volume and building location (Curado et al., 2020; Madureira et al., 2016b), were also determining of indoor radon levels in the schools studied. The number of occupants could lead to a higher need to use natural ventilation and indirectly influence indoor radon levels.

For ozone (O_3), the outdoor environment was the only source of indoor levels mentioned (Cabovská et al., 2022; Jovanović et al., 2014; Sá et al., 2017), with indoor concentrations being lower than outdoors. Ventilation systems play a key role (south-facing windows and facing the street with higher levels) (Cabovská et al., 2022; Jovanović et al., 2014; Sá et al., 2017).

Exceeding available national legislation and recommendations (health-based guidelines) was not reported in most of the studies. Nevertheless, and considering the reduced availability of legislation and recommendations in some countries, exceedance was reported in some studies: Portugal ($PM_{2.5}$, PM_{10}, CO, radon) (Faria et al., 2020; Madureira et al., 2016b; Sá et al., 2017), Serbia (formaldehyde) (Jovanović et al., 2014), Poland ($PM_{2.5}$, PM_{10}) (Polednik, 2013; Połednik, 2013) and

Malta ($PM_{2.5}$, PM_{10}) (Fsadni et al., 2018). However, regarding CO_2 indoor concentrations, several studies referred the exceedance of recommended levels in different countries: Albania (Hänninen et al., 2017), Italy (L Schibuola and Tambani, 2020; Stabile et al., 2016), Kosovo (Ukëhaxhaj et al., 2023), Poland (Polednik, 2013), Portugal (J. Madureira et al., 2016; Joana Madureira et al., 2016c; Sá et al., 2017), Serbia (Lazović et al., 2015; Turanjanin et al., 2014), Slovakia (Mečiarová et al., 2018), and Slovenia (Muhič and Muhič, 2022).

3.3. Homes

This review also focused on homes, due to the potential exposure of all the population groups (infants, children, adults, elderly). The sources and determinants of the presence and concentration of indoor air pollutants are described in the Table 2.

In the context of homes, studies have identified occupancy as the main source of CO_2 (Coggins et al., 2022; Feliciano et al., 2022; Ferreira and Barros, 2022; Foster et al., 2016; Gabriel et al., 2021; Gábor Géczi et al., 2018; González Serrano and Licina, 2022; Madureira et al., 2016a; Ramalho et al., 2015), and the number of individuals directly influencing indoor CO_2 concentrations (Brown et al., 2015; Feliciano et al., 2022; Ferreira and Barros, 2022; Foster et al., 2016; Gabriel et al., 2021; Madureira et al., 2016a). Additionally, it has been recognized that fireplaces (Feliciano et al., 2022), cooking and combustion processes (Feliciano et al., 2022; Ferreira and Barros, 2022; González Serrano and Licina, 2022; Ramalho et al., 2015; Vu et al., 2022) contribute significantly to indoor CO_2 release, underscoring their impact on indoor air quality. Furthermore, ventilation conditions and the type of ventilation system have been identified as a major determinant of CO_2 concentrations (Alegría-Sala et al., 2022; Coggins et al., 2022; Du et al., 2015; Feliciano et al., 2022; Ferreira and Barros, 2022; Foster et al., 2016; Gabriel et al., 2021; Géczi et al., 2018; González Serrano and Licina, 2022; Madureira et al., 2015; Madureira et al., 2016a; Pietrogrande et al., 2021; Ramalho et al., 2015; Vu et al., 2022), alongside with factors such as house type (Justo Alonso et al., 2022; Ramalho et al., 2015), room volume (Coggins et al., 2022) and building's characteristics (e.g., location, insulation, structure) (Du et al., 2015; Géczi et al., 2018; Madureira et al., 2016a; Ramalho et al., 2015). Seasonal variations and outdoor conditions were also identified as determinants of indoor CO_2 concentrations showing an influence of outdoor air on indoor air characteristics (Alegría-Sala et al., 2022; Justo Alonso et al., 2022; Ramalho et al., 2015).

In homes the most relevant indoor sources of VOCs identified were furniture (Coggins et al., 2022; Mečiarová et al., 2017), combustion (Vilčeková et al., 2017), occupancy (Pietrogrande et al., 2021), cleaning products and consumer products (Feliciano et al., 2022; Gabriel et al., 2021; Heeley-Hill et al., 2021; Mečiarová et al., 2017; Ninyà et al., 2022; Pietrogrande et al., 2021). Other sources identified were smoking (Stamatelopoulou et al., 2019; Vilčeková et al., 2017), paints and coatings (Mečiarová et al., 2017), textiles (Coggins et al., 2022), candles (Feliciano et al., 2022), renovation work (Vilčeková et al., 2017) and construction materials (Mečiarová et al., 2017). Outdoor sources are also major contributors to indoor VOCs levels, especially for benzene, ethylbenzene, xylene, propanal, n-decane and n-dodecane, pentanal, benzaldehyde, and limonene (Kozielska et al., 2020; Villanueva et al., 2015). Ventilation was, by far, the most frequently identified determinant factor as, depending on the frequency and type, it can either help dissipate VOCs produced indoor or allow penetration from outdoor sources (Brown et al., 2015; Coggins et al., 2022; Dallongeville et al., 2016; Du et al., 2015; Feliciano et al., 2022; Justo Alonso et al., 2022; Madureira et al., 2016a; Mečiarová et al., 2017; Stamatelopoulou et al., 2019; Villanueva et al., 2015). Age of furnishings (Villanueva et al., 2015), number of occupants (Brown et al., 2015), heating systems (Mečiarová et al., 2017; Vilčeková et al., 2017), or frequency of both cleaning and use of cleaning products (Heeley-Hill et al., 2021; Ninyà et al., 2022; Stamatelopoulou et al., 2019) were also recognized as determinant, although in fewer studies. Building location was also a frequently identified as determinant factor, as the outdoor environment is an important source (Villanueva et al., 2015).

Regarding formaldehyde, several sources were identified as contributing to indoor concentrations, including furniture and wood-based materials (Birmili et al., 2022; Coggins et al., 2022; Ferreira and Barros, 2022; Villanueva et al., 2015), use of candles or incense (Gabriel et al., 2021; Justo Alonso et al., 2022), cooking (Justo Alonso et al., 2022), combustion processes (Justo Alonso et al., 2022; Ramalho et al., 2015), smoking (Villanueva et al., 2015), textiles (Coggins et al., 2022), and paints (Ferreira and Barros, 2022). Moreover, as seen before, ventilation type was identified as a determinant of indoor levels of formaldehyde (Brown et al., 2015; Dallongeville et al., 2016; Justo Alonso et al., 2022; Ramalho et al., 2015; Villanueva et al., 2015), as well as building characteristics (e.g., year of construction, location, house type) (Birmili et al., 2022; Brown et al., 2015; Du et al., 2015; Gabriel et al., 2021; Ramalho et al., 2015) and environmental parameters (e.g., temperature and relative humidity) (Brown et al., 2015; Gabriel et al., 2021; Justo Alonso et al., 2022).

For NO_2 two studies reported outdoor sources as the main contributors for indoor NO_2 and, as such, ventilation, insulation, and location of the house were identified as the main determinants that can affect indoor levels (Cibella et al., 2015; Du et al., 2015; Gabriel et al., 2021; Vu et al., 2022). One study also found a significant contribution of indoor sources to indoor concentrations of NO_2, especially cooking activities (Vu et al., 2022).

Concerning particulate matter, most of the studies examined the presence of particulate matter sized 2.5 μm and 10 μm. Additionally, four studies quantified the presence of 0.1 μm particles (ultrafine particles) (de Gennaro et al., 2015; Gabriel et al., 2021; Madureira et al., 2020; Zauli Sajani et al., 2016), while one study identified the presence of 1.0 μm particles (Stamatelopoulou et al., 2019). The main sources identified for indoor levels of $PM_{0.1}$, $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were cooking and smoking (Aquilina and Camilleri, 2022; Calama-González et al., 2019; Coggins et al., 2022; Custódio et al., 2014; de Gennaro et al., 2015; Du et al., 2015; Faria et al., 2020; Feliciano et al., 2022; Gabriel et al., 2021; Johnes et al., 2023; Madureira et al., 2020; Pietrogrande et al., 2021; Sánchez-Soberón et al., 2019; Scibor, 2019; Siponen et al., 2019; Stamatelopoulou et al., 2019; Vilčeková et al., 2017; Vu et al., 2022). Moreover, the outdoor environment and traffic emissions were recognized as contributing factors for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, alongside with the burning of candles or incense (Coggins et al., 2022; Du et al., 2015; Faria et al., 2020; Ferreira and Barros, 2022; Gabriel et al., 2021; Madureira et al., 2016a; Madureira et al., 2020; Pietrogrande et al., 2021; Scibor, 2019; Siponen et al., 2019; Zauli Sajani et al., 2016). Other indoor sources of PM_{10} and $PM_{2.5}$ include combustion processes (Custódio et al., 2014; de Gennaro et al., 2013; Feliciano et al., 2022; González Serrano and Licina, 2022; Madureira et al., 2016a; Madureira et al., 2020; Maher et al., 2021; Pietrogrande et al., 2021; Siponen et al., 2019; Stamatelopoulou et al., 2019; Vu et al., 2022), organic sources such as skin fragments, hair, dandruff, indoor plants and pets (Gabriel et al., 2021; González Serrano and Licina, 2022; Madureira et al., 2020; Pietrogrande et al., 2021; Scibor, 2019), as well as resuspension due to human movement (Aquilina and Camilleri, 2022; Brown et al., 2015; Custódio et al., 2014; Madureira et al., 2020; Stamatelopoulou et al., 2019) and cleaning practices such as sweeping (Aquilina and Camilleri, 2022; Faria et al., 2020; Feliciano et al., 2022; González Serrano and Licina, 2022; Madureira et al., 2016a; Pietrogrande et al., 2021; Stamatelopoulou et al., 2019). Ventilation continues to emerge as a critical factor in determining indoor levels of particles of all sizes (Aquilina and Camilleri, 2022; de Gennaro et al., 2013; Du et al., 2015; Feliciano et al., 2022; Ferreira and Barros, 2022; Madureira et al., 2016a; Madureira et al., 2020; Scibor, 2019; Stamatelopoulou et al., 2019; Vu et al., 2022). Various determinants of pollutants' presence and concentration related to building characteristics, including building orientation, floor level, location, room volume and house type (apartment, single or multi-

Table 2
Sources, concentrations, and determinants of indoor air pollutants presence in homes.

Indoor air pollutant	Sources	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants	References
CO_2	Occupancy Cooking Fireplace Combustion Smoking	569–2116 ppm	1540–2892 ppm	Yes 2/15 studies	Number of occupants Type of ventilation (natural, mechanical) House type Season Building' characteristics (structure, insulation, location) Room volume Environmental parameters	(Alegría-Sala et al., 2022; Coggins et al., 2022; Du et al., 2015; Feliciano et al., 2022; Ferreira and Barros, 2022; Foster et al., 2016; Gabriel et al., 2021; Géczi et al., 2018; González Serrano and Licina, 2022; Justo Alonso et al., 2022; Madureira et al., 2015; Madureira et al., 2016a; Pietrogrande et al., 2021; Ramalho et al., 2015; Vu et al., 2022)
Total VOC	Occupancy Cleaning products Consumer products Smoking Renovations Combustion Furniture Textiles Candles/incense Construction materials Paints/solvents/coatings Organic sources (pets) Cleaning	50–2610 μg/m^3	604–14,690 μg/m^3	Yes 1/11 studies	Type of ventilation (natural, mechanical) Environmental parameters Heating system House type Building' characteristics (age, insulation, location) Mold/dampness Floor type Cleaning products – frequency of use Consumer products – frequency of use	(Coggins et al., 2022; Du et al., 2015; Feliciano et al., 2022; Gabriel et al., 2021; Heeley-Hill et al., 2021; Justo Alonso et al., 2022; Madureira et al., 2016a; Mečiarová et al., 2017; Ninyà et al., 2022; Pietrogrande et al., 2021; Stamatelopoulou et al., 2019; Vilčeková et al., 2017; Wang et al., 2023; Yang et al., 2020)
Benzene	Combustion Smoking Outdoor environment Occupancy	1.1–4.7 μg/m^3	1.3–22.8 μg/m^3	No safe level.	Number of occupants Type of ventilation (natural, mechanical) Building' characteristics (age)	(Brown et al., 2015; Dallongeville et al., 2016; Kozielska et al., 2020; Ramalho et al., 2015; Villanueva et al., 2015)
Toluene	Combustion Textiles Construction materials Paints/solvents/coatings Occupancy	12–25.9 μg/m^3	87.9–398.5 μg/m^3	Not available	Number of occupants Type of ventilation Building' characteristics (age)	(Brown et al., 2015; Villanueva et al., 2015)
Ethylbenzene	Combustion Outdoor environment Occupancy	3.2–3.4 μg/m^3	13–33.6 μg/m^3	Not available	Number of occupants Type of ventilation (natural, mechanical) Building' characteristics (age, location)	(Brown et al., 2015; Villanueva et al., 2015)
Xylene	Combustion Occupancy	4.18–5.44 μg/m^3	29.2–30.4 μg/m^3	Not available	Number of occupants Type of ventilation (natural, mechanical) Building' characteristics (location)	(Brown et al., 2015)
o-xylene	Outdoor environment Paints/solvents/coatings	0.8–4.4 μg/m^3	3.1–47.1 μg/m^3	Not available	Building' characteristics (location)	(Villanueva et al., 2015)
Limonene	Outdoor environment	17.1–49 μg/m^3	87.2–278 μg/m^3	Not available	Building' characteristics (location) Ventilation	(Dallongeville et al., 2016; Villanueva et al., 2015)
Pinene	Furniture	6.6–18.5 μg/m^3	54.1–63.1 μg/m^3	Not available	Furniture' characteristics (age) Ventilation Seasonality	(Dallongeville et al., 2016; Heeley-Hill et al., 2021; Villanueva et al., 2015)
Styrene	No sources identified	1.2–2.1 μg/m^3	1.3–6.5 μg/m^3	Not available	Building' characteristics (age) Ventilation	(Madureira et al., 2016a; Villanueva et al., 2015)
Acetaldehyde	Smoking Candles/incense Furniture	2.4–23 μg/m^3	2.9–94.6 μg/m^3	Not available	Building' characteristics (age, location) Type of ventilation (natural, mechanical)	(Wolfram Birmili et al., 2022; Brown et al., 2015; Gabriel et al., 2021)

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Indoor air pollutant	Sources	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants	References
Propanal	Outdoor environment Furniture	0.5–5.2 μg/m^3	0.9–23 μg/m^3	Not available	Furniture' characteristics (age)	(Villanueva et al., 2015)
N-decane	Outdoor environment	10.7 μg/m^3	141 μg/m^3	Not available	No determinants identified	(Villanueva et al., 2015)
N-dodecane	Outdoor environment	24.3 μg/m^3	116.5 μg/m^3	Not available	Building' characteristics (location)	(Villanueva et al., 2015)
Benzaldehyde	Outdoor environment	0.2–1.8 μg/m^3	0.2–12.1 μg/m^3	Not available	Building' characteristics (location) Ventilation	(Dallongeville et al., 2016; Villanueva et al., 2015)
Acetone	Furniture	50.9 μg/m^3	196 μg/m^3	Not available	Furniture' characteristics (age)	(Villanueva et al., 2015)
Butanal	Furniture Cleaning products	4.5–36 μg/m^3	4.6–88.7 μg/m^3	Not available	Furniture' characteristics (age) Cleaning products – frequency of use	(Nicole Ninyà et al., 2022; Villanueva et al., 2015)
Hexanal	Smoking Furniture Cleaning products	7.9–56.1 μg/m^3	7.9–174.9 μg/m^3	Not available	Ventilation Furniture' characteristics (age) Cleaning products – frequency of use	(Wolfram Birmili et al., 2022; Ninyà et al., 2022; Villanueva et al., 2015)
Pentanal	Outdoor environment Cleaning products	1.8–16.4 μg/m^3	1.8–45.5 μg/m^3	Not available	Ventilation Cleaning products – frequency of use	(Ninyà et al., 2022; Villanueva et al., 2015)
Diethylphthalate	No sources identified	244 ng/m^3	2900 ng/m^3	Not available	Ventilation	(Dallongeville et al., 2016)
Diethylhexylphthalate	No sources identified	36 ng/m^3	189 ng/m^3	Not available	Ventilation	(Dallongeville et al., 2016)
Diisobutylphthalate	No sources identified	699 ng/m^3	8560 ng/m^3	Not available	Ventilation	(Dallongeville et al., 2016)
Dibutylphthalate	No sources identified	102 ng/m^3	527 ng/m^3	Not available	Ventilation	(Dallongeville et al., 2016)
Formaldehyde	Occupancy Smoking Furniture Candles/incense Wood stove Cooking Combustion	7.4–54.6 μg/m^3	8.8–86.3 μg/m^3	Yes (1/10 studies)	Number of occupants Ventilation Type of ventilation (natural, mechanical) House type Season	(Birmili et al., 2022; Brown et al., 2015; Coggins et al., 2022; Dallongeville et al., 2016; Du et al., 2015; Ferreira and Barros, 2022; Gabriel et al., 2021; Justo Alonso et al., 2022; Ramalho et al., 2015; Villanueva et al., 2015)
NO_2	Cooking Outdoor environment	14.2–31.9 μg/m^3	136–147.6 μg/m^3	Not available	Ventilation Building' characteristics (location, insulation) Type of ventilation	(Du et al., 2015; Gabriel et al., 2021; Vu et al., 2022)
$PM_{0.1}$	Cooking Smoking Traffic Outdoor environment Candles/incense Textiles Cleaning	2200–14,337 part/cm^3	3544–54,083 part/cm^3	Not available	Heating system Ventilation Room volume Building' characteristics (orientation) Cleaning frequency	(de Gennaro et al., 2015; M F Gabriel et al., 2021; Madureira et al., 2020; Zauli Sajani et al., 2016)
PM_1	Smoking Cooking Resuspension (cleaning activities, human movement) Paint/solvents/ coatings	8.1 μg/m^3	134 μg/m^3	Not available	Type of ventilation (natural, mechanical) Cleaning frequency Number of windows	(A. Stamatelopoulou et al., 2019)
$PM_{2.5}$	Outdoor environment Traffic Cooking Cleaning Combustion Occupancy Smoking Candles/incense Organic (pets, skin fragments, hair, dandruff) Clothing	5–89 μg/m^3	66.7–568 μg/m^3	Yes 9/22 studies	Number of occupants Ventilation Type of ventilation (natural, mechanical) House type Building' characteristics (location, orientation, structure, insulation, age) Floor level Season Heating system	(Aquilina and Camilleri, 2022; Brown et al., 2015; A M Coggins et al., 2022; Du et al., 2015; T. Faria et al., 2020; Feliciano et al., 2022; Ferreira and Barros, 2022; M F Gabriel et al., 2021; V González Serrano and Licina, 2022; Johnes et al., 2023; Madureira et al., 2020; Joana Madureira et al., 2016a; Maher et al., 2021; Pietrogrande et al., 2021; Ramalho et al., 2015; Scibor, 2019; Siponen et al., 2019; A. Stamatelopoulou et al., 2019; Vilčeková

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Table 2 (*continued*)

Indoor air pollutant	Sources	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants	References
	Resuspension (cleaning activities, human movement) Construction materials Renovations Paints/solvents/coatings				Fuel type Cooking (device, method)	et al., 2017; Vu et al., 2022; Zauli Sajani et al., 2016)
PM_{10}	Outdoor environment Traffic Cooking Cleaning Combustion Occupancy Smoking Candles/incense Organic sources (pets, plants, skin fragments) Clothing Resuspension (cleaning activities and human movement) Construction materials Renovations	8–74.6 μg/m^3	132.9–722.9 μg/m^3	Yes 5/13 studies	Number of occupants Type of ventilation (natural, mechanical) House type Building' characteristics (location, orientation, structure, insulation, age) Season Room volume Cooking (device, method) Floor level Type of fuel Humidifier Heating system	(Aquilina and Camilleri, 2022; Baloch et al., 2020; Custódio et al., 2014; de Gennaro et al., 2015; Du et al., 2015; Faria et al., 2020; Ferreira and Barros, 2022; Gabriel et al., 2021; González Serrano and Licina, 2022; Madureira et al., 2020; Maher et al., 2021; Ramalho et al., 2015; Scibor, 2019; Stamatelopoulou et al., 2019; Vilčeková et al., 2017)
Radon	Geogenic Outdoor environment Soil	27.5–2100 Bq/m^3	149–2321 Bq/m^3	Yes 3/13 studies	Type of ventilation (natural, mechanical) Seepage from the ground Floor level Building's insulation Season Building' characteristics (location, orientation, structure, insulation, age) House type Room volume	(Antignani et al., 2021; Bräuner et al., 2013; Coggins et al., 2022; Du et al., 2015; García-Tobar, 2019; G Géczi et al., 2018; Kourtidis et al., 2015; Kropat et al., 2014; McCarron et al., 2019; McCarron et al., 2020a; Mezquita et al., 2019; Pietrogrande et al., 2021; Vukotic et al., 2019; Walczak et al., 2020)
CO	Smoking Combustion	0.1-0.6 ppm	1.1–23 ppm	Yes 1/2 studies	Heating system Ventilation	(Feliciano et al., 2022; Gabriel et al., 2021)
O_3	Outdoor environment	5.9–6.2 μg/m^3	32–41.3 μg/m^3	Not available	Cleaning products Air freshners	(Siponen et al., 2019)
BC	Cooking Resuspension (cleaning activities) Candle/incense	1 μg/m^3	62.3 μg/m^3	Not available	Cooking method Ventilation	(Aquilina and Camilleri, 2022)
Thoron	Geogenic Construction materials	216 Bq/m^3	406 Bq/m^3	Not available	Season	(Gulan et al., 2014)
PAHs, NPAHs	Traffic Combustion	9.4 μg/g	2.4–51.7 μg/g	Not available	Proximity to traffic Heating system Ventilation Room volume	(de Gennaro et al., 2015; Rutkowski et al., 2019)

CO_2 = Carbon dioxide; VOC=Volatile Organic Compounds; PM = Particulate Matter; CO=Carbon Monoxide; NO_2 = Nitrogen Dioxide; O_3 = Ozone; BC = Black Carbon; PAHs = Polycyclic Aromatic Hydrocarbon; NPAH=Nitrated polynuclear aromatic hydrocarbons

family house) were identified (Brown et al., 2015; Du et al., 2015; Faria et al., 2020; Ferreira and Barros, 2022; Gabriel et al., 2021; Madureira et al., 2020; Ramalho et al., 2015; Scibor, 2019; Siponen et al., 2019; Vilčeková et al., 2017; Zauli Sajani et al., 2016). The heating system also affected particulate matter levels (de Gennaro et al., 2015; Feliciano et al., 2022; Scibor, 2019; Vilčeková et al., 2017), along with the number of occupants present in the indoor environment (Pietrogrande et al., 2021; Ramalho et al., 2015).

As radon is a natural occurring gas that can penetrate into houses, ventilation and insulation are major determinants in indoor concentrations (Antignani et al., 2021; Du et al., 2015; Gábor Géczi et al., 2018; McCarron et al., 2020a; McCarron et al., 2019; Vukotic et al., 2019). As it can also penetrate from the ground beneath buildings, the floor level and building foundation were also identified as determinants for higher levels on the ground floor (Du et al., 2015). House type also influences radon concentration with single-family houses showing higher levels than apartments (Kropat et al., 2014). This emphasizes the need for buildings to have solid concrete foundations (Kourtidis et al., 2015). Other building' characteristics such as age, location and structure were also identified as determinants factors of indoor radon concentration levels (Bräuner et al., 2013; Kourtidis et al., 2015; Kropat et al., 2014; Mezquita et al., 2019). Thoron, a radioactive isotope of radon, was also identified in a study in Kosovo where geogenic sources and construction materials were identified as sources (Gulan et al., 2014).

Regarding other pollutants such as CO, smoking and combustion were the sources identified along with the heating system and ventilation as factors influencing indoor concentrations (Feliciano et al., 2022; Gabriel et al., 2021). For ozone, outdoor environment was referred as a source, and the use of cleaning products and air freshners were appointed as influencing negatively the ozone concentration due to the release of limonene and α-pinene that react with O_3 (Gabriel et al., 2021). One study assessed the presence of black carbon (BC) by identifying cooking, resuspension from cleaning activities such as sweeping and use of candles or incense as sources (Aquilina and Camilleri, 2022). Ventilation and cooking methods were highlighted as important determinants (Aquilina and Camilleri, 2022). Regarding PAHs and NPAHs, traffic and combustion processes were the sources of indoor levels identified, and proximity to traffic emerged as a significant determinant, while factors such as ventilation, heating systems and room volume were also considered (de Gennaro et al., 2015; Rutkowski et al., 2019).

3.4. Lecture halls

Table 3 describes the main sources and determinants of indoor pollutants in lecture halls. Lecture halls are indoor areas, larger than typical classrooms, in universities. Because of their size, the potential exposure of students and staff working in this type of facility can be relevant for a large group of people.

As mentioned above, few studies are available for this specific setting. The lecture halls are large rooms that accommodate a high number of people indoors, making the evaluation of indoor air quality very relevant. The sources of indoor air pollutants identified in these studies are like those above mentioned for schools and homes: smoking for formaldehyde (Hu et al., 2022), occupancy for CO_2 (Alegría-Sala et al., 2022; Hu et al., 2022; Ragazzi et al., 2019), geogenic sources for radon (Arias-Ferreiro et al., 2021; Azara et al., 2018; Calvente et al., 2021; Kozak et al., 2013) and the outdoor environment influencing indoor pollution levels (Kovacevic et al., 2015; Majewski et al., 2018; Majewski et al., 2016). In terms of determinants, the importance of ventilation stands out, identified in several studies as a factor influencing indoor pollutants levels.

3.5. Hospitals

Table 4 describes the main sources and determinants of indoor pollutants present in hospitals. It is important to emphasize that in a hospital there are two distinct groups of individuals who are affected by a possible low indoor air quality: the patients (who are occasionally inside the facilities being treated for their health conditions and, therefore, present an inherent vulnerability); and the healthcare professionals (who are exposed in an occupational context and daily). The present study retrieved eight studies in hospitals, thus this setting is likely still understudied. Occupancy was again identified as the main source of CO_2 (Baurès et al., 2020; Loupa et al., 2016; Stamp et al., 2020), $PM_{2.5}$ (Loupa et al., 2016; Scheepers et al., 2017; Stamp et al., 2020) and total VOCs (Hyttinen et al., 2021; Rautiainen et al., 2019; Scheepers et al., 2017; Stamp et al., 2020), in accordance with the other settings mentioned above. The same authors identified the number of occupants as an important factor influencing the concentration of indoor pollutants ($PM_{2.5}$ and CO_2). For total VOCs, extended assessments were performed in hospitals with measurements and detection of many VOCs. Overall, the concentration of total VOCs in hospitals were below 200 μg/m^3, besides some specific situations detailed below. Several sources of VOCs were identified such as occupancy, cleaning products, disinfectants, and pharmaceutical products, and the following factors influenced indoor concentrations and were therefore identified as determinants: ventilation (mechanical), air exchange rate (inverse correlation with indoor concentrations), location in the room, room characteristics (area, volume), furniture (number of pieces). The existence of sparsely decorated hospital rooms combined with an efficient ventilation system is pointed out as an indoor environment with low VOCs levels (Hyttinen et al., 2021). The presence of xylenes was particularly determined in the pathology laboratories, as it is used during samples processing, with the highest concentration determined (3390 μg/m^3) (Hyttinen et al., 2021). In a broader perspective, for VOCs, the existence of mechanical ventilation was a determinant of indoor air concentrations identified for most compounds.

For radon, the presence of this pollutant was assessed in a study conducted in Bari (Italy), and most workplaces (76.1 %) reported radon concentrations within the WHO reference value (100 Bq/m^3). The higher levels ($>$ 148 Bq/m^3) were determined in basement rooms, which means that floor level is a determinant of indoor air radon concentrations (Vimercati et al., 2018).

Table 3
Sources, concentrations, and determinants of exposure to indoor air pollution in lecture halls.

Indoor air pollutant	Sources	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants	References
CO_2	Occupancy	1716 ppm	5000 ppm	Yes 1/3 studies	Number of occupants Type of ventilation (natural)	(Alegría-Sala et al., 2022; Hu et al., 2022; Ragazzi et al., 2019)
Formaldehyde	Smoking	13.3 μg/m^3	Not reported	Yes (National target: 10 μg/m^3)	Number of occupants Type of ventilation (natural) Room volume	(Hu et al., 2022)
PAHs	Combustion Traffic Outdoor environment	6.8–13.0 ng/m^3	Not reported	Not available	Type of ventilation (mechanical)	(Majewski et al., 2018)
$PM_{1.0}$	Outdoor environment	9.5–14.5 μg/m^3	Not reported	Not referred	Type of ventilation	(Kovacevic et al., 2015; Majewski et al., 2016)
PM_{10}	Resuspension	47 μg/m^3	Not reported	Not referred	Type of ventilation	(Kovacevic et al., 2015)
Radon	Geogenic Construction materials Soil	12–1521 Bq/m^3	38–265 Bq/m^3	1/4 studies	Number of occupants Type of ventilation (natural) Building' characteristics (age) Floor level Seepage from the ground	(Arias-Ferreiro et al., 2021; Azara et al., 2018; Calvente et al., 2021; Kozak et al., 2013)

CO_2 = Carbon dioxide; PM = Particulate Matter; CO=Carbon Monoxide; PAHs = Polycyclic Aromatic Hydrocarbon

Table 4
Sources, concentrations, and determinants of indoor air pollutants presence in hospitals.

Indoor air pollutant	Sources	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants	References
CO_2	Occupancy Human activities	451–480 ppm	Not reported	No	Number of occupants Period of the day Ventilation	(Baurès et al., 2020; Loupa et al., 2016; Stamp et al., 2020)
Total VOCs	Occupancy Cleaning products Disinfectants Pharmaceutical products Oxidizing compounds	33.1–2449 μg/m^3	170–9287 μg/m^3	No	Ventilation (mechanical) Air exchange rate Room characteristics (area, volume) Furniture (number of pieces)	(Hyttinen et al., 2021; Rautiainen et al., 2019; Scheepers et al., 2017; Stamp et al., 2020)
Acetone	Adhesive remover	1–28.4 μg/m^3	Not reported	Not available	No determinants identified	(Baurès et al., 2020)
Pinene	No sources identified	1.8 μg/m^3	10 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Benzene	No sources identified	1.2 μg/m^3	2.9 μg/m^3	No safe level.	Ventilation (mechanical)	(Rautiainen et al., 2019)
Benzyl alcohol	Disinfectants	1.2–1.5 μg/m^3	2.3–4.3 μg/m^3	Not available	Ventilation (mechanical) Air exchange rate	(Hyttinen et al., 2021)
BTEX (benzene, toluene, ethylbenzene, xylene)	Laboratory reagents Traffic	12.8 μg/m^3	Not reported	Not reported	Ventilation (natural and mechanical) Building structure Thermal insulation Automatized laboratory systems	(Cipolla et al., 2017)
Decamethyl-cyclopentasiloxane	No sources identified	3.9–8.1 μg/m^3	18–140 μg/m^3	Not available	Ventilation (mechanical) Air exchange rate	(Hyttinen et al., 2021; Rautiainen et al., 2019)
Hexamethyl-cyclotrisiloxane	No sources identified	2.3–4.1 μg/m^3	5.1–20 μg/m^3	Not available	Ventilation (mechanical) Air exchange rate	(Hyttinen et al., 2021; Rautiainen et al., 2019)
Octamethyl-cyclotetrasiloxane	No sources identified	1.4–3.6 μg/m^3	5.3–16 μg/m^3	Not available	Ventilation (mechanical) Air exchange rate	(Hyttinen et al., 2021)
DBP - Dibutyl phthalate	Floor Building materials	30–80 μg/m^3	10–190 μg/m^3	Not available	Season	(Baurès et al., 2020)
DEHP -bis(2-ethylhexyl) phthalate	Floor Building materials	10–30 μg/m^3	30–70 μg/m^3	Not available	Season	(Baurès et al., 2020)
DEP – Diethyl phthalate	Floor Building materials	10–130 μg/m^3	140–260 μg/m^3	Not available	Season	(Baurès et al., 2020)
Decanal	No sources identified	2.7 μg/m^3	7.3 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Dodecane	No sources identified	2.4 μg/m^3	15 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Ether	Adhesive remover	6.0–19.3 μg/m^3	Not reported	Not available	No determinants identified	(Baurès et al., 2020)
Ethanol	Disinfectants	0.5–942.9 μg/m^3	Not reported	Not available	Ventilation (mechanical) Air exchange rate	(Hyttinen et al., 2021)
Ethylbenzene	No sources identified	31 μg/m^3	850 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Heptane	No sources identified	1.2 μg/m^3	3.6 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Hexene	No sources identified	2.6 μg/m^3	11 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Limonene	Cleaning products	0.8–12.3 μg/m^3	Not reported	Not available	Ventilation (mechanical)	(Baurès et al., 2020; Rautiainen et al., 2019)
Nonanal	No sources identified	2.2 μg/m^3	6.6 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Nonane	No sources identified	2.3 μg/m^3	5.5 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Octane	No sources identified	3.7 μg/m^3	14 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Other aliphatic hydrocarbons	No sources identified	6.1 μg/m^3	16 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Phenol	Disinfectants	0.3–0.8 μg/m^3	Not reported	Not available	Ventilation (mechanical) Air exchange rate	(Hyttinen et al., 2021)
Toluene	No sources identified	0.8–32.9 μg/m^3	2.5–39 μg/m^3	Not available	Ventilation (mechanical)	(Baurès et al., 2018; Hyttinen et al., 2021; Rautiainen et al.,

(continued on next page)

Table 4 (*continued*)

Indoor air pollutant	Sources	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants	References
						2019; Scheepers et al., 2017; Stamp et al., 2020)
TXIB (2,2,4-trimethyl-1,3-pentanediol di-isobutyrate)	No sources identified	0.5–1.7 μg/m^3	Not reported	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
Xylene	Laboratory reagents	0.2–110 μg/m^3	0.5–3390 μg/m^3	Not available	No determinants identified	(Rautiainen et al., 2019)
1-butanol	Solvents Adhesives Hygiene products Disinfectants	18 μg/m^3	240 μg/m^3	Not available	Ventilation (mechanical) Type of floor	(Rautiainen et al., 2019)
2-ethyl-1-hexanol	Disinfectants	1.1 μg/m^3	3 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
2-methyl-1-propanol	Cleaning products Disinfectants	2.3 μg/m^3	5.8 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
2-methyl-2-propanol	Disinfectants	22 μg/m^3	105 μg/m^3	Not available	Ventilation (mechanical)	(Rautiainen et al., 2019)
NO_2	Traffic	4.9–20.4 μg/m^3	30.2 μg/m^3	Not available	Ventilation (mechanical) Period of the day	(Stamp et al., 2020)
Formaldehyde	Outdoor environment	2.6–21.7 μg/m^3	6.3 μg/m^3	No	No determinants identified	(Scheepers et al., 2017)
$PM_{2.5}$	Occupancy Human activities Medical devices Medication Fragrances	1.3–18.6 μg/m^3	Not reported	No	Ventilation (mechanical and natural) Number of occupants Operation of medical devices	(Loupa et al., 2016; Scheepers et al., 2017; Stamp et al., 2020)
BC	Outdoor environment	1.0–1.2 μg/m^3	Not reported	Not available	Ventilation (mechanical and natural) Period of the day	(Loupa et al., 2016)
Radon	Soil	35.8–55.0 Bq/m^3	147.5–538 μg/m^3	0.9 % > 300 q/m3	Ventilation Floor level	(Vimercati et al., 2018)

CO_2 = Carbon dioxide; VOC=Volatile Organic Compounds; PM = Particulate Matter; CO=Carbon Monoxide; NO_2 = Nitrogen Dioxide; O_3 = Ozone; BC = Black Carbon

3.6. Other settings

This section addresses the results of the settings with fewest studies considered eligible for this review: retirement homes ($n = 5$), public transports ($n = 4$) and canteens ($n = 1$). Table 5 describes the main sources and determinants of indoor pollutants. In general, these studies identified few sources and determinants of indoor pollutants. For retirement homes, the studies identified traffic and occupancy, resuspension due to human movements, soil and cleaning products as sources of $PM_{2.5}$ and PM_{10}. Building location was also a determinant of indoor pollutant concentrations, as facilities near to the airport and the sea, were affected by outdoor sources (Almeida-Silva et al., 2015, 2016). Occupancy and number of occupants were also identified in this setting as a source and determinant, respectively (Almeida-Silva et al., 2016; Almeida-Silva et al., 2015; Almeida et al., 2016; Madureira et al., 2015; Mendes et al., 2016).

For public transports, studies were conducted in metro ($n = 3$) and tram ($n = 1$). As expected, occupancy was identified as a source of indoor CO_2 concentrations and the number of people in the carriage as a determinant of these concentrations (Baselga et al., 2022). Regarding PM, occupancy and resuspension were the sources identified for PM_{10} (Faria et al., 2020; Grydaki et al., 2021), while mechanical wear was identified as the source for $PM_{2.5}$ (Moreno et al., 2015), which leads to train frequency being an important determinant of indoor PM concentrations (Grydaki et al., 2021; Moreno et al., 2015).

The study conducted in a university canteen concluded that commercial cooking emissions are an important source of air pollutant gases. Cooking procedures were identified as the main source of VOC, in particular benzene and formaldehyde, with ventilation and the type of cooking device having a strong influence on indoor concentrations (gas or electric stoves representing lower indoor concentrations compared to barbecue grilling) (Alves et al., 2015).

4. Discussion

This review provides a comprehensive overview of indoor air quality in Europe over the last decade. Several settings (schools, homes, hospitals, retirement homes, public transport, lecture halls), under consideration in K-HEALTHinAIR project (www.k-healthinair.eu), were included in the present review with the common characteristic of being scenarios in which individuals spend a large part of their daily lives. An important aspect of indoor air quality is knowing the sources of pollutant emissions of and the factors that influence their presence indoors, the determinants. A deep knowledge on these two aspects will allow better solutions to be deployed to improve indoor air quality.

The research conducted in the last decade and reviewed in the present manuscript highlights another important aspect, i.e., the reduced number of studies that performed a detailed and robust statistical analysis to identify the sources and the determinants of the presence of indoor air pollutants. Nevertheless, 37 % of studies in schools, 46 % of studies in homes, and 38 % of studies in hospitals, performed a statistical analysis to establish an association between sources and pollutants and to identify the determinants of indoor concentrations. Statistical methods varied from inferential tests such as Mann-Whitney, Kruskal-Wallis, to more complex analysis using Principal Component Analysis, linear mixed effects and multivariate regression models. On the one hand, these characteristics emphasize the need to conduct detailed data collection in indoor environments, which then allows to perform a robust and complex analysis and draw conclusions sufficiently strong weight of evidence. On the other hand, these results allowed us to

Table 5
Sources, concentrations, and determinants of exposure to indoor air pollution in retirement homes, transports and canteens.

Indoor air pollutant	Sources	Concentration (range of means)	Concentration (range of maximums)	Exceedance of national legislation	Determinants	References
Retirement homes						
CO_2	Occupancy	1033 ppm	2697 ppm	Yes 1/2 studies	Ventilation Number of occupants Season	(Madureira et al., 2015; Mendes et al., 2016)
Total VOC	No sources identified	48–78 μg/m^3	931–973 μg/m^3	Yes	Season	(Mendes et al., 2016)
$PM_{2.5}$	Traffic	63 μg/m^3	952 μg/m^3	Not referred	No determinants identified	(Mendes et al., 2016)
PM_{10}	Occupancy Resuspension Cleaning products Organic sources (soil) Traffic Sea spray	10.9–29.0 μg/m^3	86–1730 μg/m^3	No	Ventilation (mechanical, natural) Number of occupants Building (location)	(Almeida-Silva et al., 2015, 2016; Almeida et al., 2016)
Transports						
CO_2	Occupancy	685 ppm	Not reported	No	Ventilation (mechanical, natural) Number of occupants	(Baselga et al., 2022)
$PM_{2.5}$	Mechanical wear	29–72 μg/m^3	Not reported	Not referred	No determinants identified	(Moreno et al., 2015)
PM_{10}	Occupancy Resuspension	53-84 μg/m^3	Not reported	Yes 1/2 studies	Frequency of trains	(Bouillon et al., 2023; T. Faria et al., 2020; Grydaki et al., 2021)
Canteen						
Benzene	Cooking	0.6–2.2 μg/Nm^3	Not reported	Not available	Ventilation (mechanical) Cooking device	(Alves et al., 2015)
Formaldehyde	Cooking	6.5–10.7 μg/Nm^3	Not reported	Not reported	Ventilation (mechanical) Cooking device	(Alves et al., 2015)

CO_2 = Carbon dioxide; VOC=Volatile Organic Compounds; PM = Particulate Matter.

recognize the complexity of this field, the difficulty in collecting accurate, reliable and useful data on indoor air quality, including contextual data, and this may partially explain the absence of a harmonized legislation in larger geographic areas, such as, Europe.

As part of this review, it was possible to identify the sources and determinants of indoor pollutants for several scenarios. Regarding CO_2, occupancy was a common source across all scenarios, with further contribution of cooking, smoking, and fireplaces (combustion) in homes. Ventilation and the number of occupants were the main determinants identified as influencing the indoor CO_2 concentrations. It has been recognized before that the control of CO_2 indoors is a challenge, despite the installation of ventilation systems (López et al., 2023). Regarding PM, occupancy, resuspension, human activities (cleaning, cooking, craft, use of chalk), organic sources (pets, molds, soil), clothes, construction materials and traffic, were identified as sources of exposure. The number of occupants, the ventilation, and the characteristics of buildings (especially regarding construction materials) played an important role for the levels of PM indoors. This identification is fundamental for the implementation of preventive measures to reduce human exposure in indoor settings, since PM are deleterious for health, especially the smaller sizes that can be inhaled and absorbed (Bo et al., 2017; Zhang et al., 2021). The installation of air conditioners with high-performance filter systems together with air purifiers to neutralize fine dust should be considered, especially if the outdoor air is strongly affected by traffic-intensive roads, airports or industrial areas (Pulimeno et al., 2020).

Regarding VOCs, cleaning activities, craft activities, disinfectants and furniture were identified as sources of indoors VOC (e.g., formaldehyde, limonene, pinene). In hospitals, some laboratories were identified as hotspots, related to the use of xylene and formaldehyde, similar to more recent findings in this setting (Riveron et al., 2023).

In terms of measures to prevent the presence of these pollutants indoors, we could consider the Hierarchy of Controls approach described in some EU regulations dedicated to Occupational Hygiene issues (European Commission, 2004). This approach provides a framework for determining ways to implement systems or controls (from most effective to least effective) to prevent/control exposure, starting with the elimination or substitution by a less hazardous process or toxic substances. In the case of indoor air quality, our goal is to prevent the presence of the indoors pollutants and, if elimination is not possible, to reduce (control) their presence. One option could also be a combination of these two actions, i.e., prevention and reduction. Preventive actions could be either on the regulatory or the technical level. For the former, a good example is the restrictions established in the EU under the scope of Registration, Evaluation, Authorisation and Restriction of Chemicals (1907/2006/ECD – REACH) that limits the presence of substances, such as formaldehyde, in certain construction products and materials (e.g. furniture that contains wood or other materials used indoors) (European Commission, 2023). At a technical level, we can refer to correct thermal insulation of building with a good isolation of the materials used in the construction process. In both cases we aim to eliminate the presence of indoor pollutants.

In the case of reduction (or control) we can point to measures such as an effective ventilation and the selection of low-emission products starting from building materials to furniture, other household or office equipment and cleaning products. In combination with these, we can also put in place administrative controls such as limiting the number of occupants in each indoor space and/or providing guidance on how/when to use the natural/mechanical ventilation or even defining strict schedules for developing cleaning procedures and listing the cleaning products allowed to be used.

All these actions should be chosen based on specific aspects of the indoor settings. For instance, schools and hospitals imply higher risks due to higher vulnerability of certain groups of occupants and users or are more prone to the presence of specific pollutants (e.g. VOCs in schools and hospitals), although with different sources of exposure.

Relevant is the fact that some of the measures already implemented in the EU, mainly those related with regulatory actions, need to be evaluated to allow concluding on effectiveness or need for revision, and future research projects should tackle this need (Dimitroulopoulou et al., 2023). As mentioned by Settimo et al. (2020), several guidelines, orientations and regulations have been published by several entities aiming to improve the indoor air quality; nevertheless, there is no harmonized regulation in the European region that defines limits for indoor air pollutants similar to those of the Air Quality Directive available for outdoor air, despite being recognized as an important determinant of health (Settimo et al., 2020; Toyinbo et al., 2022). Although not being in the scope of the review, but one aspect that should be also emphasized is the lack of harmonization in research protocols and sampling methods across all the studies eligible for this review. Despite ISO 16000:2004 and WHO described the sampling strategy and methods available, including the conditions to be observed for the substances, the sampling strategy used in the studies eligible for this review presented several variations (e.g., passive methods or active methods, point measurements or continuous measurements, type of equipment, the duration of sampling), hampering the comparison of results between different studies (ISO, 2004; WHO, 2020). The development of harmonized research protocols, guidelines and legislation emerge has a need for the near future of IAQ area to ensure that meaningful comparisons, thus confirming the priorities previously identified by other authors (Saffell and Nehr, 2023; Siddique et al., 2023).

This review comprised several indoor scenarios and the most recent period of 10 years, thus giving an updated perspective of this field, some limitations should be mentioned. The time frame as criteria left out of the scope of this review studies conducted before 2013. Several studies did not conduct a statistical analysis to attribute the source of indoor pollutants and to analyse the determinants, relying on available literature and previous knowledge.

5. Conclusions

Within this review it was possible to identify the most important emission sources and determinants of the presence of indoor pollutants in settings where people spend most of their time. In schools, the main indoor sources of indoor pollutants were determined to be the occupants, cleaning products, wood materials and electronic equipment, and school activities (use of chalk, textiles, physical activity), with the outdoor sources being also important contributors for the presence of pollutants indoors. The ventilation systems and the number of occupants (e.g., students) in the rooms were the main factors determining the presence of indoor pollutants. The results obtained for lecture halls are aligned with the ones obtained for schools regarding the sources and determinants of exposure. In homes, the main sources of indoor pollutants were related with activities such as the cooking, cleaning and burning candles and/or incenses, as well as organic sources such as pets, hairs, molds. The type of heating system plays also an important role, with combustion systems contributing more for the presence of indoor pollutants. Similarly to the findings in schools, the ventilation and the number of residents were the main factors determining the presence of indoor pollutants. Results obtained for retirement homes and canteens are aligned with the ones found for homes. In hospitals, the main sources were occupancy, human activities, disinfectants, laboratory reagents and floor, while the ventilation and number of occupants were again determinant for the concentration of indoor pollutants. For public transports, occupancy was an important source as well as aspects related to the infrastructure (e.g., mechanical wear in trains and subway). The present review made also possible to discuss some of the actions that are already in place or should be implemented in the future to prevent and control the presence of pollutants indoors, and mostly importantly to recognize some of the research gaps that need to be addressed in future or ongoing research projects.

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CRediT authorship contribution statement

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Data availability

Data will be made available on request.

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