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PANDORA: An open-access database of indoor pollutant emission rates for IAQ modeling

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ABSTRACT

Modeling indoor air quality requires reliable data on pollutant emission rates (ERs) from indoor sources. While many studies focus on measuring indoor pollutant concentrations, far fewer provide the source-specific ERs needed for predictive modeling, and those that do often report fragmented and non-standardized formats that limit their use. This paper addresses this gap by introducing PANDORA (a comPilAtioN of inDOor aiR pollutAnt emissions), an internet-based open-access database designed to improve consistency and transparency in indoor air quality assessments. PANDORA systematically compiles ERs data for gaseous and particulate pollutants from a wide range of indoor sources. It classifies 747 sources into comprehensive categories such as construction and decoration materials (354), furniture (38), cleaning products and air fresheners (123), occupants and occupant activities (134), heating and cooking appliances (48), electrical equipment (40), whole room or building (6) and others (4). In this paper, we summarize key experimental methods used to assess the pollutants. To aid in informed decision-making, statistical analyses are provided for selected indoor pollutants of interest, including $PM_{2.5}$,

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formaldehyde, benzene, and TVOC. Additionally, we compare the impact of using three different modeling approaches and assumptions through a case study that uses the PANDORA data to evaluate indoor pollutant ERs in a room. This application shows how PANDORA supports more transparent and consistent use of emission rate data. Our findings highlight that, despite compiling 9968 emission rate entries, expanding PANDORA with new measurements will further strengthen the accuracy and reliability of indoor air quality modeling and exposure assessments.

1. Introduction

Models to predict the Indoor air quality (IAQ) in a room require diverse input data, including building envelope leakage information, weather conditions, ventilation system characteristics, contaminant source emission rates, sink removal rates, occupant schedules, and air cleaner removal rates. Reed and Polidoro [1] highlighted that while much of this data is available in the literature, it is rarely compiled into a readily accessible source. They concluded that to streamline the IAQ modeling process and enable the assessment of data quality and completeness, there is an urgent need for well-designed databases of measured contaminant modeling data. Since emission rates of pollutant sources are also typical input data that are not readily available, this led to the creation in 2009 of the PANDORA (a com**P**il**A**tion of i**ND**o**OR** **A**ir pollutant emissions) database [2]. This is a database that systematically compiles available data on the emission rates of both gaseous and particulate pollutants, providing valuable information for IAQ modelers.

The PANDORA database did not start from scratch. Over the past 25 years, several databases and technical reports regarding pollutant emissions of indoor sources, especially on VOCs emissions, have been created: SOPHIE database [3], the California Integrated Waste Management Board (CIWMB) report for school construction materials [4], the Canadian MEDB-IAQ database [5] or the European BUMA database [6]. However, these efforts were tied to specific projects with limited timeframes and funding, leading to the interruption of data implementation and database maintenance once the projects ended. PANDORA might have faced a similar fate if not for the developers' awareness of the scientific community's need for such data to advance IAQ assessments, including the evaluation of ventilation system performance. Within the framework of the International Energy Agency EBC - Annex 86 - Energy Efficient Indoor Air Quality Management in Residential Buildings, PANDORA has been updated in terms of accessibility and available data. In 2021, a significant development transformed the original downloadable MS Access file into an internet-based database accessible on all devices, including phones, tablets, and desktops, through the dedicated website https://db-pandora.univ-lr.fr/. Additionally, participants of Annex 86 Subtask 2 identified new data through a literature review for integration into the database. As a result, approximately 1000 new entries were added to the 9000 already implemented by 2024.

This paper presents the PANDORA database, developed to address limitations in how emission rate data are reported and used in IAQ modelling, making it a practical and expandable tool for researchers and practitioners working in IAQ and environmental health. The first section provides summaries of all references from which the data were sourced by looking for reported pollutant emission rates of indoor sources from journal and conference peer-reviewed papers and reports from trustworthy authorities. All those references were categorized into seven types of sources and include details such as the studied sources, experimental chamber dimensions, environmental conditions, and measured pollutants. The second section focuses on the database itself, detailing its structure, how emission rates are stored, and how individual and statistical data can be accessed. Finally, section 4 presents a case study on the application of the database to evaluate the emission rates of a room and discusses its role in improving the accuracy and transparency of exposure assessments.

2. Literature-based data compilation

The data implementation was carried out in three phases: the first, during the creation of the database in 2009, involved integrating all data published before that date. The second phase consisted of gradually implementing data until 2014. Finally, more recently, as part of the Annex86 project, a collection of post-2014 references was compiled by indoor air quality experts. Publications were identified through Scopus, Web of Science, and Google Scholar, using keywords 'indoor air quality', 'emission rates', 'indoor pollutants'. Papers were not geographically restricted, but exclusion criteria included non-peer-reviewed studies. In this final phase, not all recorded data could be fully integrated; therefore, a selection was made to complement the various source typologies with the most recent data. The database does not claim to be exhaustive but provides a set of data intended to help indoor air quality modelers find input data for their simulations. By systematically organizing and analyzing ER data, PANDORA supports more robust indoor air quality modeling and human exposure assessments. To our knowledge, this is the most comprehensive, freely accessible compilation of indoor pollutant emission rates to date, addressing a critical barrier to harmonized IAQ modeling. Fig. 1 presents the range of scientific publications on pollutant emission rates by indoor sources that have been implemented finally in the database.

The first set of studies, published in the early 1980's, focused on emissions from heating and cooking appliances (domestic gas-fired ranges, gas-fired stoves, gas-fired unvented space heaters, kerosene-fired unvented space heaters, conventional and catalytic woodstoves). This category represents 12 % of the references collected.

In the 1990's, several studies focused on electrical equipment encountered in offices (mainly printers, photocopiers and computers) as sources of pollutants.

In 1997, Bluyssen et al. outlined the principles for assessing VOC emissions from building materials, specifically focusing on a methodology to evaluate solid flooring materials through emission factor determination. That was the start of different projects

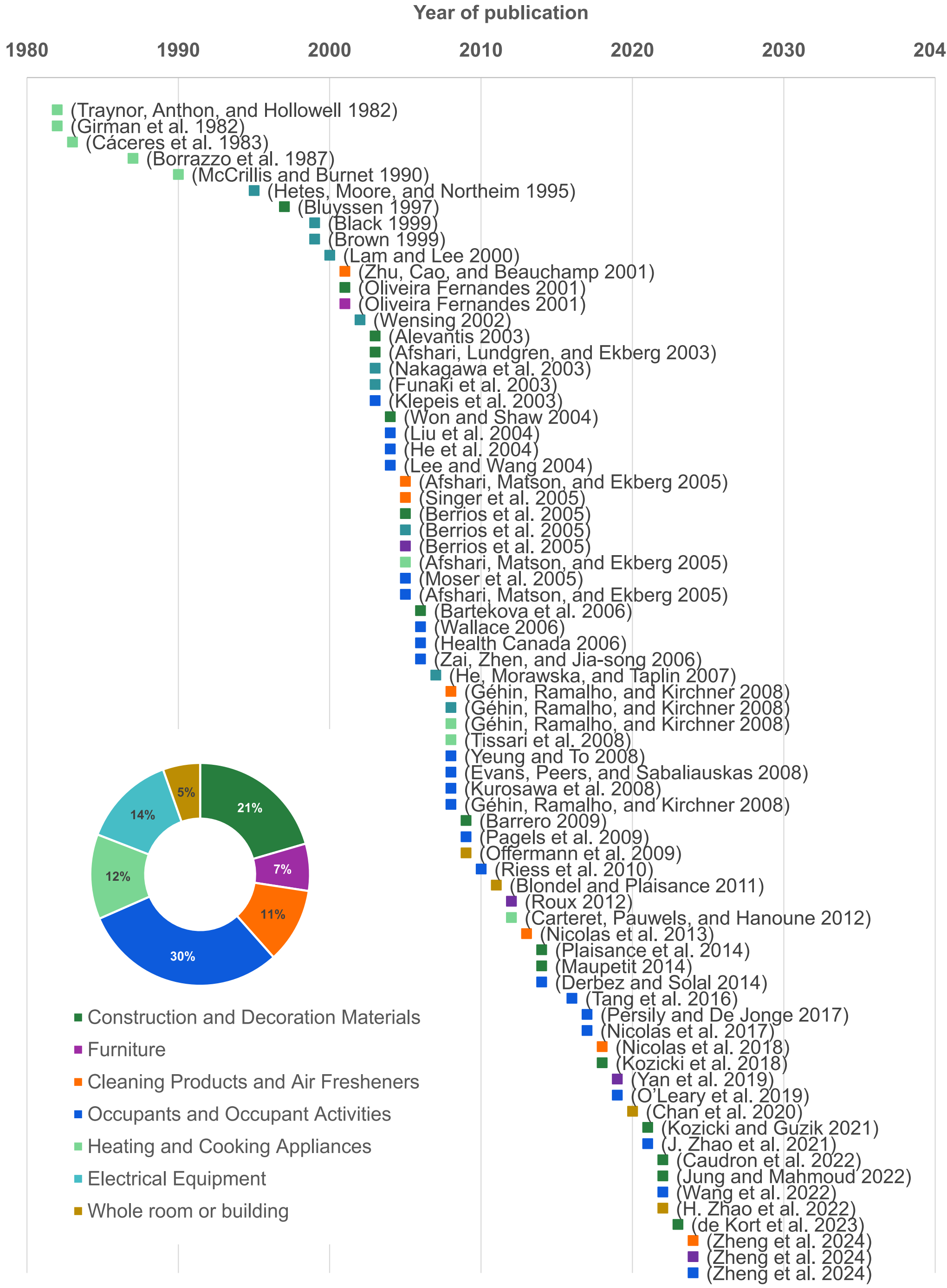

Fig. 1. Historical overview of scientific publications of emission rates in relation to the source category.

regarding the emissions of construction and decoration materials (21 % of the references) leading to the creation of databases such as the European SOPHIE [3], the Canadian MEDB-IAQ [5] or more recently the European BUMA [6].

Interest in emissions from cleaning products and air fresheners (11 % of the references) and from furniture (7 %) began in the early 2000's ([3,7]). Still, various studies focused on emissions from office electrical equipment (14 % of the references).

The study of Klepeis et al. [8] on environmental tobacco smoke (ETS) from cigars and cigarettes can be considered as the first data on sources belonging to the occupants and occupants' activities category. Many studies followed as they account for 30 % of the total references.

A last category of sources (whole room or building; 5 % of the references) appears more recently and considers the indoor spaces as a unique source. Emission rates are here evaluated from pollutant concentrations in real occupied rooms or buildings and thus provide an integrated assessment considering the interplay of multiple sources, ventilation behavior, and pollutant removal mechanisms.

Most of the scientific publications (62 %) comes from peer-reviewed scientific journals (Fig. 2). Reports from research projects account for 25 % of the identified literature including Construction and Decoration Materials data from the historical databases (SOPHIE, MEDB-IAQ or BUMA) or more recent projects on Occupants' Activities and Cleaning Products. The rest comes from international conference papers such as Indoor Air and Healthy Buildings conferences.

The following sections provide an overview of the above papers organized into the seven categories identified. They describe the approach taken to transform a large and diverse set of published emission rate data into a structured, standardized, and useable format. The method ensures that the resulting database can support consistent data selection and integration into IAQ modeling workflows. To support transparency and reuse, Section 1 of the supplemental material includes short abstracts of the referenced studies. Section 2 provides summary tables detailing the tested sources, chamber dimensions, environmental conditions, ventilation rates, measurement durations, pollutants, instrumentation used, and the type of emission rate reported.

2.1. Construction and decoration materials

Construction and decorative materials are among the most significant sources of indoor air pollution, particularly due to their emissions of volatile organic compounds (VOCs) and aldehydes. These emissions are typically high when materials are new, often peaking within the first hours or days before stabilizing overtime. The variability in emissions depends on factors such as material composition, environmental conditions, and application methods. Research in this field has focused on identifying emission characteristics, evaluating health risks, and informing the development of VOC labeling systems.

Bluyssen et al. [9] developed a procedure to assess VOC emissions from building materials, focusing on solid flooring through emission factor determination and modeling indoor VOC concentrations. Oliveira Fernandes [3] emphasized the need for low-emission materials, reporting VOC and formaldehyde emissions from various building materials. Alevantis [4] compared VOC emissions from standard and sustainable materials, with rubber-based flooring showing higher emissions. Afshari et al. [10] studied VOC emissions from paint, highlighting the role of film thickness. Won and Shaw [5] created a database for 60 building materials, aiding in the selection of low-emission products. Berrios et al. [11] found that office materials like carpet emitted fewer VOCs compared to electronic devices. Bartekova et al. [12] tested OSB and coatings, concluding they met low-emission standards. The BUMA project [6] developed an emissions database for over 400 construction materials. Plaisance et al. [13] found significant variability in carbonyl emissions from 23 materials. Maupetit [14] noted that additive models, i.e. adding individual source emission rates, overestimate emissions of all sources located in a room. Kozicki et al. [15] assessed VOC emissions from waterproofing materials, stressing the importance of ventilation. Kozicki and Guzik [16] analyzed adhesives, finding variations in emissions based on the material used. Caudron et al. [17] observed increased emissions from bio-based materials at higher humidity. Jung et al. [18] proposed formaldehyde emission models, and de Kort et al. [19] evaluated emissions from various board materials, emphasizing the differences between bio-based and synthetic options.

VOC emissions from construction and decoration materials have been the most investigated because this source has been detected as one of the most important in terms of health effects to occupants [20]. The main features of these emissions are potentially high

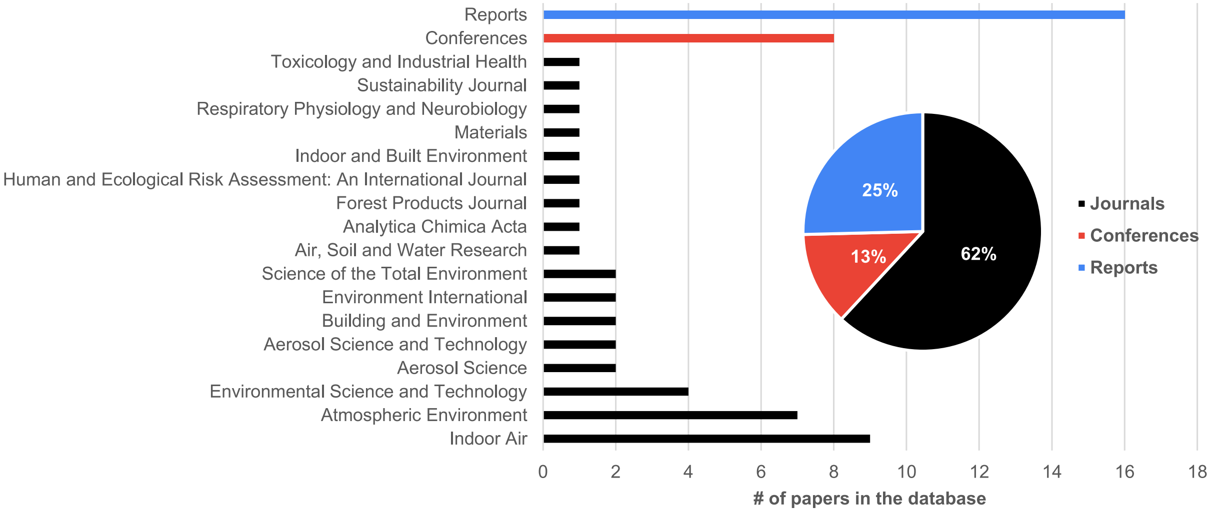

Fig. 2. Origin of data included in the PANDORA database.

emissions when materials are new within the first hours/days with rapid decreases toward stabilization or small decrease after about one month. This led various countries to adopt their own VOC labeling systems to tackle this important source of long-term exposure in buildings, ranging from mandatory (France, Japan, CARB in the U.S.) to voluntary eco-labels (Blue Angel in Germany, M1 in Finland, Sweden, Denmark and Norway, EMICODE in EU). The choice of certification depends on regional regulations, product type, and IAQ goals. The methodology involves placing a material sample in a small chamber under controlled temperature (°C), relative humidity (%), and fresh air circulation (ACH). The measurement continues until pollutant concentrations in the air stabilize or after a specified period (typically 28 days). These stabilized concentrations are then used to classify the material into different categories based on target pollutants like aldehydes (such as formaldehyde, acetaldehyde) and VOCs (including toluene, xylenes, TVOCs).

2.2. Furniture

Furniture can be a significant source of indoor air pollution due to the release of volatile organic compounds (VOCs). These emissions vary depending on the type of furniture, materials used, and environmental conditions. Research on furniture emissions primarily focuses on VOCs, often using controlled experimental setups to quantify emissions under standardized conditions.

Oliveira Fernandes [3] summarized VOC emissions from indoor sources in the SOPHIE database, highlighting tests on cushions using small chambers under controlled conditions (23 ± 1 °C, 45 ± 5 % RH) and measuring VOCs and formaldehyde emissions. Berrios et al. [11] analyzed emissions from passive (e.g., desks, chairs) and active (e.g., printers, PCs) sources in office settings, finding negligible TVOC emissions from furniture compared to other indoor sources. Roux [21] measured VOCs and aldehydes from 21 nursery furniture pieces and 38 furniture components, noting generally low emissions with variable results depending on complete furniture or components. Yan et al. [22] studied a foot stool and bedside table, finding VOC emissions peaked within 1–2 h and identified health risks from xylene exposure. Zheng et al. [23] examined emissions during daycare activities, especially from mattresses, under different conditions, revealing critical chronic health risks for young occupants, with emission patterns influenced by product type and age.

Studies on furniture emissions are mainly based on VOCs, each study covering different components with different methodologies, kind of chambers, fresh air supply rate, and duration of measurements. The tests were done with similar controlled temperature and relative humidity (23 °C and 45–50 %RH), except for the study of Zheng et al. [23], that specifically tested in cold and dry, warm and humid conditions. Two of the studies also analyze the impact on health, and two of them highlight the impact on children from their vulnerability, highlighting the need for age-specific health risk measurements of VOCs in furniture.

Like various construction and decoration materials, VOC labeling systems for furniture have emerged in recent years. In the United States, the Business and Institutional Furniture Manufacturers Association standards, such as ANSI/BIFMA M7.1 and ANSI/BIFMA X7.1, establish test methods and emission limits for office furniture, including seating and workstations, with a particular focus on formaldehyde emissions. In the European Union, several national and regional initiatives address furniture emissions in line with the European Ecolabel for furniture and mattresses. Notable examples include Germany's Blue Angel certification, which enforces strict VOC emission limits for furniture, and the Nordic Swan Ecolabel, which assesses the environmental impact of furniture across its entire lifecycle, including VOC emissions, to promote sustainable and low-emission products.

2.3. Cleaning products and air fresheners

Cleaning products and air fresheners are significant contributors to indoor air pollution, emitting VOCs and fine particulate matter. These emissions can undergo chemical reactions with ozone (O3) to form harmful secondary pollutants, such as formaldehyde and secondary organic aerosols (SOAs) ([7,24]). Terpenes like limonene and α-pinene, often present in scented products, are particularly reactive, with ozone exacerbating pollutant formation ([25,26]).

Research has identified key emission components and factors influencing pollutant levels. Zhu et al. [7] identified 2-butoxyethanol as a key VOC in cleaning products, while Singer et al. [24] demonstrated that dilution reduces VOC emissions. Afshari et al. [27] and Géhin et al. [28] highlighted significant spikes in ultrafine particles during cleaning, especially in the 5–40 nm range. Nicolas et al. [29] emphasized the variability in emissions from commercial and homemade products, while Zheng et al. [23] showed how brand, temperature, and humidity influence emission profiles. Proper ventilation, diluted usage, and avoiding ozone-generating devices are critical mitigation strategies.

Despite consensus on the impact of product composition, application methods, and ventilation rates, studies vary in their estimates of emission magnitudes, partly due to differences in methodologies (e.g., chamber sizes, analytical instruments). This underscores the need for standardized protocols when quantifying emissions. While health risks from typical usage scenarios are often considered moderate, exposures can reach concerning levels in poorly ventilated spaces.

Mitigation strategies include optimizing product formulations, using diluted solutions, enhancing air exchange, and minimizing the use of ozone-generating devices. However, research gaps persist, especially regarding long-term exposure outcomes, the combined effects of multiple VOCs, and the specific reaction pathways that yield secondary pollutants like formaldehyde and SOAs. While current guidelines recommend proper ventilation and dilution to mitigate exposure, further investigations should focus on clarifying long-term health impacts, refining emission models, and evaluating novel product formulations with reduced pollutant profiles. Such efforts would facilitate the development of evidence-based policies and best practices to safeguard human health in indoor environments.

2.4. Occupants and occupant activities

Occupants, their activities (cooking, smoking, incense and candle burning, cleaning and personal care sprays, and occupants themselves) and consumer products (TV, shoes) are major contributors to indoor air pollution, introducing a diverse range of pollutants depending on the type, duration, and frequency of activities. Various experimental approaches – including environmental chambers, test houses, and real-world monitoring – have been employed to quantify occupant-associated emissions of particulate matter (PM), volatile organic compounds (VOCs), and combustion byproducts.

He et al. [30] measured $PM_{2.5}$ emission rates from residential activities in Brisbane, linking elevated concentrations to specific behaviors with up to 3, 30 and 90 times higher than the background levels during smoking, frying and grilling, respectively. Wallace [31] reported particle concentrations from different cooking types, revealing substantial variations in particle mass emissions from cooking with a gas stove, toasting with electric toasters and toaster ovens, burning candles and incense, and using a gas-powered clothes dryer.

Specifically on cooking emissions, Yeung et al. [32] explored cooking-related particle emissions, estimating emission rates for Chinese and Western cooking styles. Evans et al. [33] examined fume production from frying, noting significant differences among homes. Géhin et al. [28] measured particle emissions from residential activities, finding ultrafine particles from cooking and cleaning. O'Leary et al. [34] studied cooking emissions in Dutch homes, noting reductions higher than 90 % with cooker hoods.

Klepeis et al. [8] developed a model to estimate particle emission factors from indoor sources, applied to environmental tobacco smoke. Moser et al. [35] investigated exhaled VOCs, finding differences between smokers and non-smokers using PTR-MS. Afshari et al. [10] quantified particle emissions from various indoor sources, including cigarettes and candles, in a chamber experiment. Health Canada [36] analyzed tobacco emissions, comparing domestic and imported cigarettes.

Several studies have focused on the pollutant emissions produced by candles. Zai et al. [37] used emission models to quantify candle smoke particles across different burning modes. Pagels et al. [38] studied candle emissions, reporting higher mass rates of particles during sooting. Zhao et al. [39] quantified indoor source emissions in 40 German homes, highlighting candles as major contributors.

Lee and Wang [40] studied air pollutant emissions from incense burning in a controlled chamber, showing incense as a significant source of indoor pollution with levels overpassing the Hong-Kong recommended IAQ limits for office buildings and public places [41] for $PM_{2.5}$, PM_{10}, carbon monoxide, formaldehyde, and benzene. Nicolas et al. [42] investigated incense and candle emissions, finding incense produced higher levels of pollutants.

Kurosawa et al. [43] investigated organic compounds emissions from TVs and shoes, showing that VOCs (toluene, xylene, styrene and TVOC) emissions were detected but decreased rapidly in the ventilated chamber, but also identified emissions of certain SVOCs such as Butylated Hydroxytoluene. Derbez and Solal [44] and Zheng et al. [23] quantified VOC emissions from arts-and-crafts school and daycare activities such as drawing, painting, modeling and glueing.

In addition to resuspending particles and introducing pollutants through activities such as cooking or cleaning, occupants themselves are a significant source of indoor air pollution, a fact long recognized in ventilation standards, which have historically considered humans as the primary pollution source in non-industrial buildings. Riess et al. [45] assessed VOCs in exhaled breath during exercise. Tang et al. [46] quantified VOC emissions from humans, revealing a significant contribution to indoor VOC levels from compounds associated with personal care products, human metabolic rate emissions and skin oil oxidation by ozone. Persily and de Jonge [47] provided data on human CO_2 generation, critical for ventilation assessments. Wang et al. [48] measured human VOC emissions under controlled conditions, finding enhanced emissions in the presence of ozone.

Given the substantial contribution of occupant emissions, IAQ management strategies should not only address activity-related spikes in pollutants but also account for continuous human emissions. This includes optimizing ventilation strategies, employing air filtration to reduce occupant-derived pollutants, and further exploring the role of human emissions in IAQ dynamics and health implications.

2.5. Heating and cooking appliances

Heating and cooking appliances are major contributors to indoor air pollution, emitting pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), volatile organic compounds (VOCs), and particulate matter (PM). Several studies have quantified emissions from gas-fired ranges, stoves, and unvented heaters. Traynor et al. [49] quantified emissions from gas-fired ranges, demonstrating the effectiveness of an IAQ model in predicting pollutant levels. Similarly, Girman et al. [50] evaluated emissions from gas-fired stoves and unvented space heaters, highlighting the health risks associated with these appliances, particularly in poorly ventilated spaces. Cácares, Sota, and Lissi [51] measured emissions from gas and kerosene heaters, noting that predicted values often exceeded air quality standards. Borrazzo et al. [52] used mass-balance models to study CO and NO_2 emissions from gas-fired appliances in energy-efficient homes, emphasizing the role of air exchange in pollutant levels. Tissari et al. [53] compared combustion conditions in wood stoves, finding that smoldering combustion significantly increased emissions of CO, VOCs, and particulate matter.

Given their potential to significantly impact IAQ in both short and, in case of heating, long term, it is important to use proper ventilation (such as range hoods for cooking and exhaust systems for heating) and choose efficient, low-emission appliances to minimize these effects. Regular maintenance will also help reduce emissions from heating and cooking systems.

2.6. Electrical equipment

Although often overlooked, electrical and office equipment can contribute to indoor air pollution by releasing VOCs, ozone (O_3), and fine particulate matter. These emissions stem from both materials (e.g., plastic casings, inks) and operational processes. Hetes et al. [54] reported that emissions from materials (e.g., casings, inks) and operational processes increase hydrocarbon, ozone, and particulate concentrations, with dry-process photocopiers being a priority for exposure prevention. Black [55] and Brown [56] quantified emissions of VOCs, ozone, and PM_{10} from printers, photocopiers, and computers, finding laser printers emitted significantly higher VOC and ozone levels than inkjet printers. Lam and Lee [57] confirmed this disparity, identifying higher TVOC and ozone emissions from laser printers. Wensing [58] and Nakagawa et al. [59] noted decay in VOC emissions from electronics over time but consistent emissions during operation. Funaki et al. [60] demonstrated that devices like portable PCs and photo journals significantly contribute to VOC and aldehyde levels. Berrios et al. [11] linked active sources (e.g., computers, printers) to elevated TVOC levels. He et al. [30] emphasized the impact of printer types on ultrafine particle (UFP) emissions. Finally, Géhin et al. [28] highlighted fine and UFP emissions from residential activities, with negligible emissions from printers compared to other indoor sources of particles.

While electrical equipment does not typically emit high levels of pollutants comparable to cooking or heating appliances, devices such as printers or photocopiers can contribute to indoor air pollution. As a result, aiming at source control, positioning of such devices in separate, well-ventilated rooms, may limit the exposure considerably.

2.7. Whole room or building

Indoor air quality assessments often extend beyond individual sources to evaluate emissions at the room or building scale. Whole-room or whole-building studies provide a more integrated understanding of pollutant concentrations by accounting for interactions between multiple sources, ventilation dynamics, and pollutant removal processes.

Offermann et al. [61] found that homes with mechanical ventilation systems often failed to meet required standards for formaldehyde, with higher-than-expected emission rates, especially in the winter months. Blondel and Plaisance [62] measured formaldehyde emission rates from indoor materials in student residences and found that emission rates varied, with higher emissions from specific materials like beds. Chan et al. [63] provided detailed data on multiple contaminants in California homes, including $PM_{2.5}$, CO, NO_2, and formaldehyde, capturing time-varying concentrations of these pollutants and highlighting the importance of accurate emission rate measurements for assessing IAQ. Zhao et al. [64] focused on formaldehyde emissions, using a regression model to estimate emission rates across a range of homes, emphasizing that mechanical ventilation and air leakage could significantly affect emissions.

Assessing emission rates at the room or building scale by analyzing pollutant concentrations, while accounting for factors such as airflow rates, particle deposition and resuspension, and sorption effects, offers a complementary approach to identifying individual sources separately. This method has the advantage of avoiding the overestimation that can result from simply aggregating emission rates from individual sources. It also prevents unnoticed sources from being ignored. Incorporating data from this approach enables more accurate modeling of indoor source strengths, providing a representation that better reflects real-world conditions.

3. PANDORA database

3.1. Structure

The PANDORA database structure has remained unchanged since its creation in 2009. Fig. 3 presents the main sub-headings of data and the connections between them. Its main structure is based on four levels [2]:

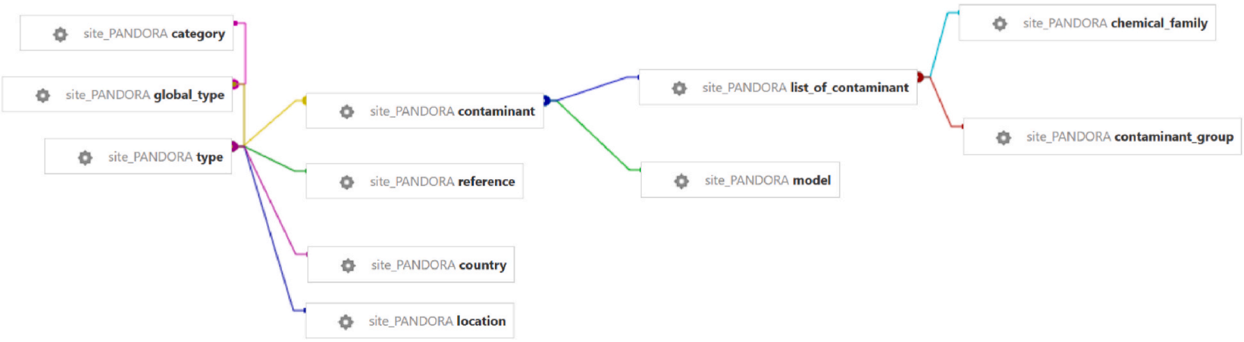

Fig. 3. PANDORA’s structure overview.

- **category**: the database structure starts with 8 main categories of indoor sources (Construction and Decoration Materials, Furniture, Cleaning Products and Air Fresheners, Occupants and Occupant Activities, Heating and Cooking Appliances, Electrical Equipment and Whole room or building).
- **global_type (or sub-category)**: the first sub-category refines the description of the indoor sources. For example, for the “Occupants and occupant activities” category, different sources are found such as body, breathing, cooking, painting, smoking, etc.
- **type (or source)**: one extra level is used to give additional information on the type of source (e.g. frying meat with oil on electric stove, frying fish on electric stove, cooking fish in electric oven, etc.) but also on the experimental protocol (duration, environmental conditions, airflow rates, quantity of products, etc.), location (residential, school, office, hospital …), country of origin and reference of the original study.
- **contaminant:** the definition of the pollutants generated by the source with their emission rates is given at this last level.

This four levels structure has been chosen to facilitate navigation into the data. However, additional information about the sources or about the experimental conditions of the emission rate measurement may be needed. Additional fields are provided in both **type** and **contaminant** categories to add comments. Therefore, The PANDORA database catalogs key indoor pollutants along with their common names, synonyms, and CAS (Chemical Abstracts Service) numbers.

One important table is the list of models (**model**) used to define the pollutant emission rates of a source. Table 1 presents the 25 models (or ways to express emission rates) included in the database accounting for the pollutant (gas or particles), the temporal dependency (steady-state or transient) and the emission rate unit. For example, VOC data for Construction and Decoration Materials are surface-specific emission rates and are usually expressed for different periods of time (model 11), while those for Occupants and Occupants’ Activities can be found relative to a use (per unit, mass of product or energy) or directly integrated as mass per time. For particles, emission rates are expressed as mass or number per time. To limit the number of models, additional calculations have been

Table 1
Pollutant emission models used in the PANDORA database.

#	Description	Equation[a]
01	Gas - Steady-State - Emission Rate (μg/unit)	$S = a$
02	Gas - Steady-State - Emission Rate (mg/h)	$S = a$
03	Gas - Steady-State - Emission Rate (mg/m^2.h)	$S = a$
04	Gas - Steady-State - Emission Rate (mg/g)	$S = a$
05	Gas - Steady-State - Emission Rate (μg/(h.person))	$S = a$
06	Gas - Steady-State - Discrete Emission Data Model - Temp/RH (μg/h)	$S(T,RH) = a_i \; at \; T_i \; and \; RH_i$
07	Gas - Steady-State - Discrete Emission Data Model - Temp/RH (μg/(h.m^2))	$S(T,RH) = a_i \; at \; T_i \; and \; RH_i$
08	Gas - Steady-State - Metabolism dependant (μg/(h.person)) [b]	$S(BMR,M) = 3197 \times BMR \times M$
09	Gas - Steady-State - T/RH - House (mg/(h.m^{2}floor)) [c]	$S(T,RH) = H \times C_s \times \frac{(1 + A \times (T - 25))(1 + B \times (RH - 25))}{\frac{1}{a_t} + \frac{1}{k \times L}}$
10	Gas - Transient - Discrete Emission Data Model (μg/h)	$S(t) = a_i \; at \; t = t_i$
11	Gas - Transient - Discrete Emission Data Model (μg/m^2.h)	$S(t) = a_i \; at \; t = t_i$
12	Gas - Transient - Discrete Emission Data Model (μg/(h.unit))	$S(t) = a_i \; at \; t = t_i$
13	Gas - Transient - Discrete Emission Data Model (μg/(h.g))	$S(t) = a_i \; at \; t = t_i$
14	Gas - Transient - Peak Model (mg/m^2.h)	$S(t) = a_1 \; e^{-0.5 \left(\frac{ln \frac{t}{t_p}}{a_2} \right)^2}$
15	Gas - Transient - Power Law Model (mg/m^2.h)	$S(t) = a_1 \times t_p^{-a_2} \; if \; t \le t_p$ $S(t) = a_1 \times t^{-a_2} \; if \; t > t_p$
16	Gas - Transient - Single Exponential Decay Model (μg/h)	$S(t) = a_1 \; e^{-a_2 t}$
17	Gas - Transient - Double Exponential Decay Model (mg/(h.m^2)))	$S(t) = a_1 \; e^{-a_2 t} + a_3 \; e^{-a_4 t}$
18	Gas - Transient - Single Exponential Growth Model (μg/h)	$S(t) = a_1 + a_2(1 - e^{-a_3 t})$
19	Gas - Transient - Steps (mg/h)	$S(t) = a_i \; if \; t(i-1) < t < t(i), t(0) = 0$
20	Particles - Steady-State - [dpmin; dpmax] (#/min)	$S(t) = a$
21	Particles - Steady-State - [dpmin; dpmax] (μg/unit)	$S(t) = a$
22	Particles - Steady-State - [dpmin; dpmax] (mg/min)	$S(t) = a$
23	Particles - Steady-State - Log-Normal Distribution (#/min)	$S(t) = \sum S_i \int \frac{1}{d_p (2\pi)^{0.5} \; ln \; GSD_i} e^{-\frac{(ln \; d_p - ln \; GMD_i)^2}{2(ln \; GSD_i)^2}} dd_p$
24	Particles - Steady-State - Log-Normal Distribution (mg/min)	$S(t) = \sum S_i \int \frac{1}{d_p (2\pi)^{0.5} \; ln \; GSD_i} e^{-\frac{(ln \; d_p - ln \; GMD_i)^2}{2(ln \; GSD_i)^2}} dd_p$
25	Particles - Transient - Steps (mg/h)	$S(t) = a_i \; if \; t(i-1) < t < t(i), t(0) = 0$

[a] S: Emission rate (unit depends on model); a: mean, min, max, median and/or standard deviation (unit depends on model); t: time (h); a_i: constants (unit depends on model); t_p: time constant (h); d_p: particle diameter (μm); GSD: Geometric Mean Diameter (μm); GSD: Geometric Standard Deviation (−).

[b] BMR: Basal Metabolic Rate (MJ/d); M: metabolic rate (met).

[c] H: ceiling height (m); A, B, and C_{st}: fitted parameters; L: effective emitting material loading rate in the house (m^2/m^3); a_t: average air exchange rate for 1 h (/h); k: mass transfer constant (m/s).

made from the original data when sufficient information was provided by the authors.

Additional libraries are updated with the integration of new data such as the **list_of_contaminants (or groups)** that provides the pollutant group (particles, volatile organic compounds, inorganic compounds, biocides, biologic pollutants and other), usual name and CAS number, the **country** library to store the geographical origin of the data, the **location** library to specify where the source is usually found (residence, school, day-care, office and all) and the **reference** library to keep track of the scientific paper or report from where the data have been extracted.

3.2. Individual data

The following graphs present the nature of the data implemented in PANDORA: almost 10,000 emission rates (ER) from literature have been integrated so far. The first studies on pollutant emission rates were published in 1982, focusing on emissions from Construction and Decoration Materials (Fig. 4). 2003 is a pivotal year with the publication of several reports from American and European projects on materials' emission of VOCs. Studies reporting emission rates from Cleaning Products, Air Fresheners and Occupants' Activities have been published since 2013.

Currently, about 65 % of the ER implemented in the database are related to the Construction and Decoration Materials, 16 % to Cleaning Products and 12 % to Occupants and Occupants' Activities.

A total of about 3000 pollutants is found in the database linked to at least one ER. Fig. 5 shows that formaldehyde is currently the most cited pollutant with 336 ERs, followed by TVOC (311), particles (173) and benzene (150). Others are related to other VOCs such as toluene, ethylbenzene, xylene … aldehydes such as acetaldehyde, benzaldehyde, butyraldehyde … and few SVOC such benzo(a) pyrene, pyrene, diethyl phthalate …

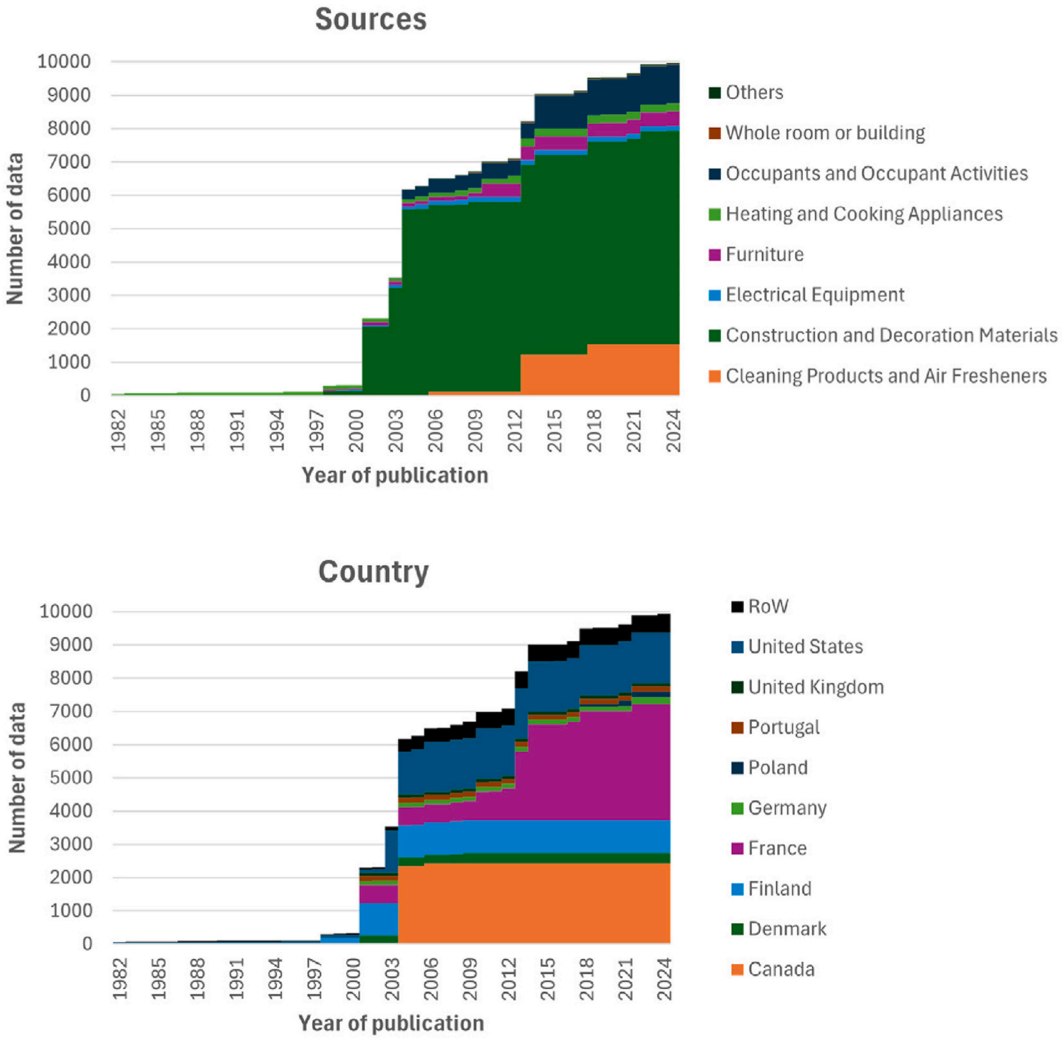

Fig. 4. Number of data (i.e. ER) implemented according to the category of indoor sources (upper graph) and country (lower graph).

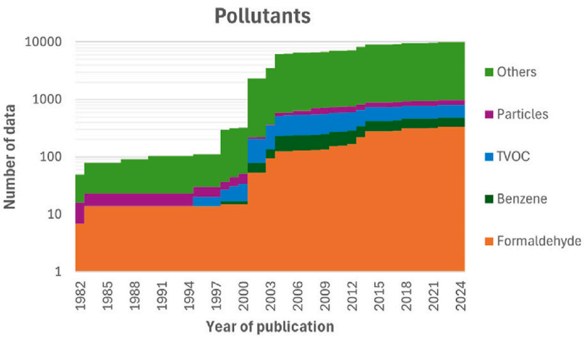

Fig. 5. Number of data (i.e. ER) implemented according to the pollutants.

Particles are expressed in terms of $PM_{2.5}$, PM_{10}, ultra-fine particles (UFP) or by size intervals. The main data sources available in PANDORA are Occupants' Activities and Heating and Cooking Appliances (Fig. 6). Formaldehyde emissions have been investigated in literature for all categories of sources, mainly for Construction and Decoration Materials, Cleaning Products and Air Fresheners and Occupants' Activities. Most of the emission rates for benzene come from Construction and Decoration Materials and Occupants' Activities. TVOCs have been mainly investigated for Construction and Decoration Materials and Electrical Equipment (mostly printers and photocopiers).

All data are accessible from the database homepage (https://db-pandora.univ-lr.fr/). Data can be searched by the source of pollutant defined by **category**, **sub-category** and **source** and/or by the pollutant of interest via its **group** and **name** or **CAS number**. Results are shown in the lower part of the webpage as tags. By clicking on the selected tag, information about the source, reference paper (on the left side) and emission rate/model (on the right side) are then displayed.

3.3. Data analysis

To provide more practical information for IAQ modelers, a dedicated companion website has been created to offer statistical analyses of certain data groups, enabling more informed decision-making. The website can be accessed through the "Data Analysis" page of the PANDORA database by clicking on the link labeled "PANDORA Statistical Analysis."

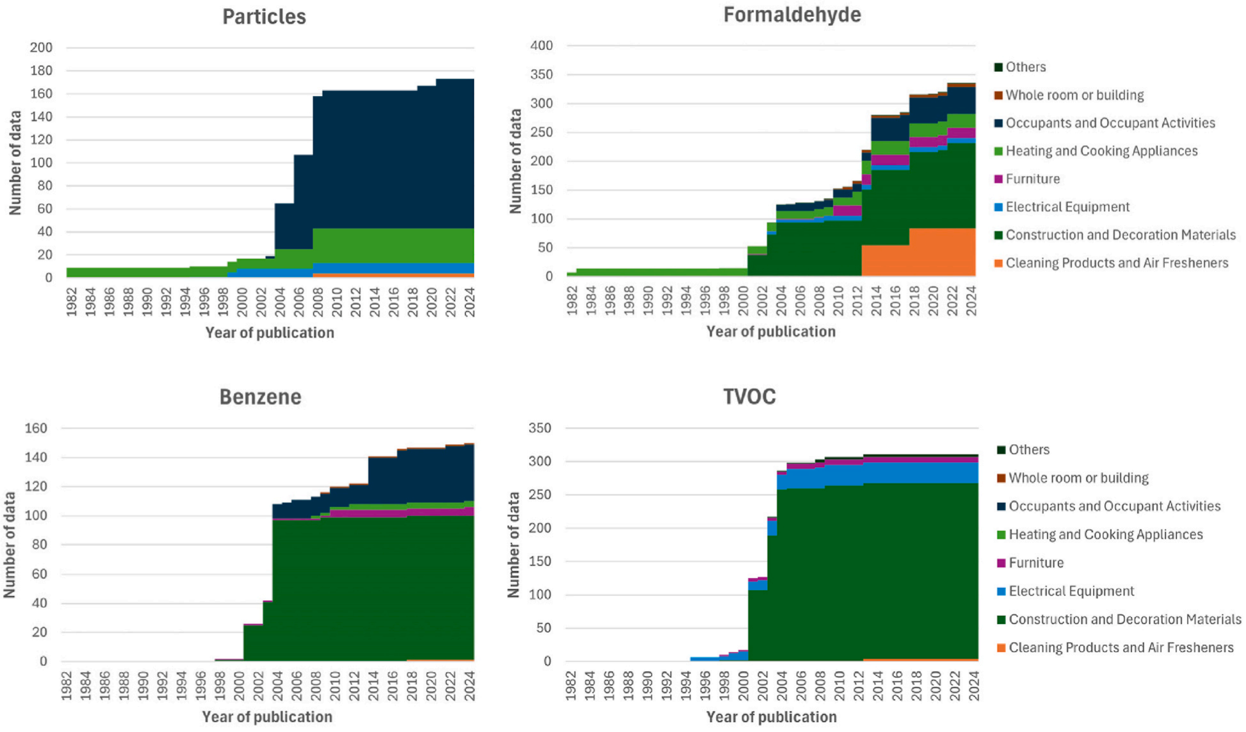

Fig. 6. Number of data (i.e. ER) implemented according to the category of indoor sources for particles, formaldehyde, benzene, and TVOC.

The analysis currently focuses on four target pollutants: $PM_{2.5}$, formaldehyde, benzene, and TVOC. For each pollutant, the data were compiled based on their primary indoor sources, namely Construction and Decoration Materials, Furniture and Occupants and Occupants' Activities (including the use of cleaning products). While most of the results presented on the webpage are straightforward compilations, the Construction and Decoration Materials category offers a more detailed analysis due to the large volume of data (65 %) available in the database. Note that the results are displayed in figures, and the associated statistics (mean, standard deviation, min., P25, median, P75 and max.) can be downloaded for external use.

3.3.1. Construction and decoration materials

The analysis results for Construction and Decoration Materials data for formaldehyde, benzene, and TVOC are presented for each sub-category using two box-plot charts. The first chart shows emission rates at 3 days, 28 days, and 365 days, while the second splits these results based on the year of data publication. Fig. 7 illustrates the case of Flooring for formaldehyde.

As previously presented, data is expressed in different ways. In the case of Construction and Decoration Materials, five models are used. The methodology to calculate the statistics at three times (3 days, 28 days, and 365 days) is the following:

- Model 03: References provide value for t = 3 days and t = 28 days only. Note that the data availability is limited, and the age of materials is often unknown.
- Models 14, 15, and 17: Calculations are performed for each time point. These equations are typically based on data for times under 30 days (sometimes extending to 60 days). Calculations for t = 365 days are extrapolated and should be interpreted with caution.
- Model 11:
  - o For t = 3 days: The closest available time point less than or equal to 3 days is used.
  - o For t = 28 days: The closest available time point less than or equal to 30 days is used (to account for the abundance of data at t = 30 days instead of t = 28 days).
  - o For t = 365 days: The closest available time point greater than 6 months is used (currently, no data for this duration are available in PANDORA).

In the previous results, sources were still separated by sub-categories i.e. Carpeting, Acoustical Materials, Finishes, Flooring, Furnishing Materials, Installation Materials, Interior Panels, Structural Materials, Insulation Materials, Wall Covering and Openings. In that way, IAQ modelers must select the emission rates corresponding to the materials composing the flooring, ceiling and vertical walls of the indoor environment they need to model. To facilitate the process of calculating a global emission rate that accounts for all those building parts, we calculate ultimate aggregated data called meta-data (Fig. 8) that is related to the geometrical surface area i.e. the sum of the floor, ceiling and vertical walls surface areas. However, in its current state, there is no dedicated field in the database to distinguish the use of a particular material for the floor, vertical walls and ceiling. As a result, all materials are applied to each one of the surfaces with the same probability. In this way, there is no dependency on the building/room dimensions. Therefore, the meta-data statistics are calculated based on one statistical value (mean or maximal) of each material category (Acoustical Materials, Carpeting …) previously calculated and the number of available data. The methodology employed here is based on the rules of the French LCA database INIES [65] to calculate default values when specific values are not available:

- If only one value is available, then the resulting value is multiplied by two.
- If two values are available, then the resulting value is the maximal value of the two available values multiplied by 1.3. This adjustment reflects a conservative estimate used in exposure assessments.
- If there are more than two available values, then the resulting value is the mean value multiplied by 1.3.

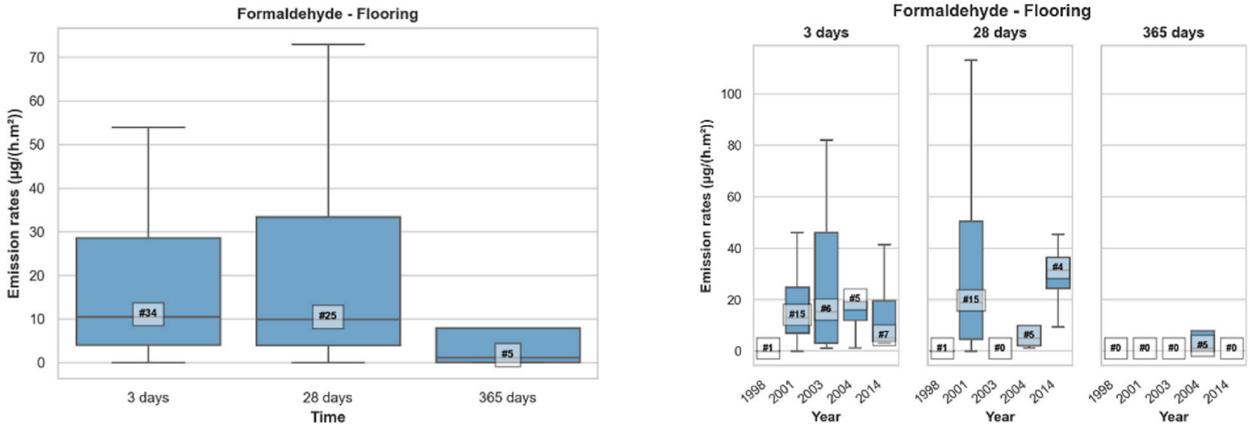

Fig. 7. Statistics of emission rates of formaldehyde for flooring after 3, 28 and 365 days (left: all data; right: separated by the year of publication).

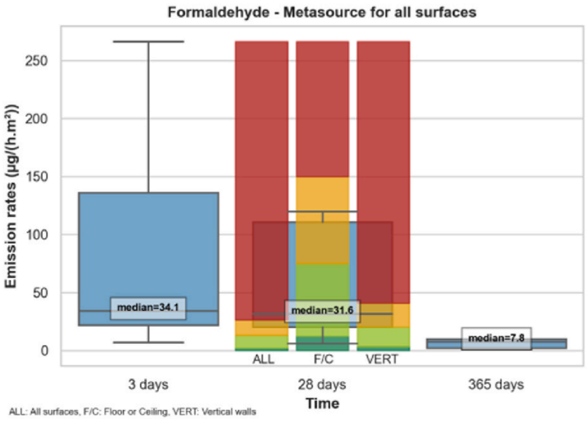

Fig. 8. Meta-data statistics of emission rates of formaldehyde after 3, 28 and 365 days (French label color-scale is displayed for comparison).

When available, the French Label color-scale for construction and decoration materials VOC emission (French Decree April 19th, 2011) is displayed for the emission at 28 days. The color code used is green (A+ = low emission), light green (A), yellow (B) and red (C = high emission). The considered room for this calculation has the following dimensions and air change rate: 4.0 × 3.0 × 2.5 m^3 and 0.5 vol/h of clean air. These calculations considered that the material is applied to all internal surfaces (ALL, 59 m^2), only the Floor or Ceiling (F/C, 12 m^2) and only vertical walls (VERT, 35 m^2).

3.3.2. *Other sources*

Since the number of available data points is insufficient to calculate statistics, all emission rates for other sources of formaldehyde, benzene, and TVOC (furniture and occupants and their activities), as well as particles expressed as $PM_{2.5}$ (occupants and their activities), are provided on the Data Analysis webpage and can be downloaded as a.txt file. Fig. 9 presents how the information is displayed for formaldehyde as an example.

4. Case study: estimating indoor formaldehyde concentrations in a bedroom using PANDORA

Bedrooms are a common indoor environment for long-term pollutant exposure. Formaldehyde, a known indoor pollutant emitted from composite wood products and furnishings, remains a relevant concern due to its health effects and persistence. This case study evaluates how three different approaches to selecting emission rate data from PANDORA influence the estimated indoor concentration of formaldehyde in a typical room scenario. Note that:

- In this case study, we will focus on formaldehyde emissions only.
- Only ER after 28 days are considered here.
- To calculate the ER for the whole room, the sum of ER for all individual sources considered in this case has been assumed. As Maupetit (2014) showed in its experiment, such simple additive models tend to overestimate emissions of all sources located in a room. As a result, the methodology applied here can be considered conservative.

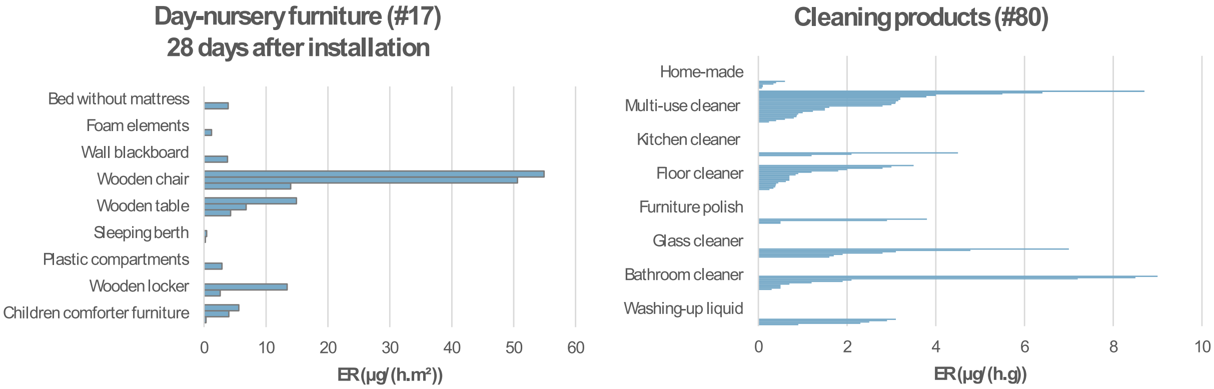

Fig. 9. Data available for formaldehyde for day-nursery furniture (left) and cleaning products (right).

4.1. Description of the room

The children's room dimensions are 4 m × 3 m × 2.5 m = 30 m^3. A carpet covers the floor while the vertical walls and ceiling are painted. The window area is 2 m^2. The following furniture is considered: one bed with its mattress, a wooden chair, a wooden table, a wooden locker, two plastic compartments and a blackboard. Because of the presence of furniture, the emitting surface area of the floor is reduced by 2.5 m^2. Also, the emitting surface area of the vertical walls is reduced by 6 m^2 because of the presence of the locker and hanging artworks and pictures. Cleaning of the furniture surfaces is supposed to be done daily.

4.2. Methods

There are three approaches to evaluate the emission rate of formaldehyde for the whole room from PANDORA (https://db-pandora.univ-lr.fr/). The first one is using the database search tool to find all individual sources and select the most appropriate ones for the studied case. The second approach is using results from statistical analysis of PANDORA's data performed during the Annex86 and working with ranges of values instead of a single ER for each source. A final alternative consists in using the so-called "Metasource" that merges altogether ER from all sources of the "Construction and Decoration Materials" category (see Table 2).

- **Approach 1**: selecting individual sources from the database

Selecting individual sources from the database search tool is the usual way of finding input data for IAQ simulation. Data can be filtered by source and pollutant. Sources are filtered according to the database structure i.e. Category, Sub-Category and Source. Pollutants can be found easier by first filtering by Pollutant Group and by the name or CAS number (in the present case, formaldehyde or 50-00-0). Note that it is recommended to clean-up the search fields by hitting the "reset filter" button between two searches. Table 3 presents the selected sources with their ER. For illustration, motivation has been added to illustrate how to select one data out of several ones.

ER for the whole room is calculated adding all products of individual ER by its emitted surface area, weighted by the duration over one day (24 h for all except for the multi-use cleaner that is supposed to emit for 2 h). The total ER for the room is **342 μg/h**. Fig. 10 compares the importance of the different sources where it can be observed that Finishes is responsible for the majority (73 %) of the emission of formaldehyde and 20 % comes from the furniture.

- **Approach 2**: using the results of statistical analysis

The companion website of PANDORA is accessible via the "Data Analysis" menu by clicking on "PANDORA Statistical Analysis" link. For formaldehyde, statistical data are available for Carpeting and Finishes for different times and split according to the year of publication of the reference papers as presented in Figs. 11 and 12 via the formaldehyde/Construction and Decoration Materials/Data section. Tabulated values corresponding to these Figures can be downloaded via the "Download data" subsection ("Formaldehyde Emission rates per types for all materials" link). Data for the Furniture and Cleaning products, displayed in Fig. 9, can be downloaded by clicking on "Formaldehyde Emission rates per types for all Furniture" and "Formaldehyde Emission rates per types for all other Sources" located in the "Furniture" and "Other Sources (Occupants)" sub-sections, respectively.

To compare the strengths of the different sources, an identical treatment has been applied to calculate the ER in terms of mass per time (μg/h) i.e. by multiplying the statistics of each source by its emitted surface area and weighted by the time of emission per day. Fig. 13 (left) presents the resulting ER for all the considered sources (for all years) of formaldehyde. As the first approach, Finishes are dominant in terms of emission. For both wall-related sources, wide ranges of values with high maximal values can be observed. This originates from the oldest data (2001) as shown in Fig. 12; more recent ones present lower ER. The graph on the right of Fig. 13 compares the results for the two approaches. To add individual ER in the second approach, we consider all the maximum, P75, P50 values individually as if the user would have chosen one level of ER to calculate the resulting value for the whole room. Because of the arbitrary choices taken in approach 1 (more recent values), its ER is in the lowest ER region of approach 2.

Table 2
Surface area of formaldehyde emission from the walls, furniture and cleaning activity.

	Surface area of formaldehyde emission (m^2)
Floor, vertical walls and ceiling	
Carpet	9.5
Finishes	64.0
Furniture	
Bed without mattress	4.5
Foam elements	2.4
Wooden chair	1.5
Wooden table	0.7
Wooden locker	6.2
Plastic compartment (2)	3.7
Blackboard	0.3
Cleaning activity	
Multi-use cleaner	5.0

Table 3
Selection of inputs from the database – Approach 1.

	Category	Sub-category	# of results	Selected Source	Motivation	ER (μg/(h.m^2))
Floor, vertical walls and ceiling						
Carpet	Construction and Decoration Materials	Carpeting	9	Carpet	Most recent data (2014)	1.9
Finishes	Construction and Decoration Materials	Finishes	8	Acrylic paint 1	Most recent data (2014) - random choice between two sources	3.9
Furniture						
Bed without mattress	Furniture	Day-nursery furniture	17	Bed without mattress (G06482B)	Only one data	3.9
Foam elements	Furniture	Day-nursery furniture	17	Foam elements (MBR 13 A)	Only one data	1.2
Wooden chair	Furniture	Day-nursery furniture	17	Wooden chair (10/2701R/5-1)	Lowest ER out of three data	14
Wooden table	Furniture	Day-nursery furniture	17	Wooden table (10/2701R/8-1)	Lowest ER out of three data	4.3
Wooden locker	Furniture	Day-nursery furniture	17	Wooden locker (MBR-05 A)	Lowest ER out of two data	2.6
Plastic compartment (2)	Furniture	Day-nursery furniture	17	Tidying up furniture with plastic compartments (MBR-17 A)	Only one data	2.9
Blackboard	Furniture	Day-nursery furniture	17	Wall blackboard (MBR 01 A)	Only one data	3.8
Cleaning activity						
Multi-use cleaner	Cleaning Products and Air Fresheners	Cleaning Products	86	Multi-purpose bleach-less cleaner – spray (PEPS21 #2)	Recent data and bleach-less	6.0[a]

[a] ER has been calculated as the average over 2 h from the data 4.0 μg/(h.g) between 0 h and 1h and 0.8 μg/(h.g) between 1 h and 2h after application. The mass of product applied is given in the information regarding the experimental methodology (2.5 g/m^2).

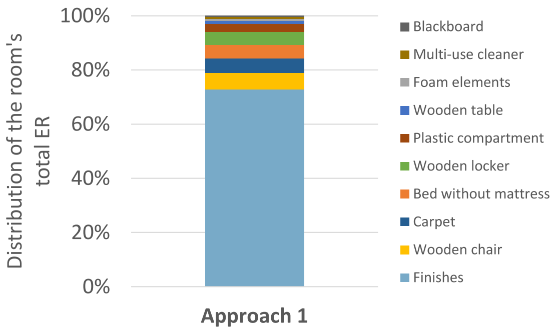

Fig. 10. Importance of the different sources based on a total ER of 342 μg/h – Approach 1.

- **Approach 3**: using the Metasource data

The Metasource data merged the Construction and Decoration Materials emission rates altogether (see section 2.2.3.1). The tabulated data can be downloaded by clicking on “Formaldehyde Meta emission rates” located in the “Meta-data” subsection of the “Construction and Decoration Materials” section for formaldehyde. Fig. 14 compares the emission rates obtained with the three approaches. Compared to the second approach, the range of variation of the data using approach 3 is slightly lower but still shows large differences between the extreme values.

4.3. Results

Fig. 15 shows the equilibrium concentration of formaldehyde using the three different methods. The equilibrium concentration refers to the level reached over time with constant ER and air exchange, specifically the emission rate divided by the airflow rate. In this case, an airflow rate of 15 m^3/h, equivalent to 0.5 air changes per hour (ACH), was selected, a common value found in bedrooms. If we account for realistic values of formaldehyde found indoors to be lower than 100 μg/m^3, one should consider the lowest values from approach 2 and 3. Even for formaldehyde, which has the largest number of emissions recorded, variation of real-world sources and their strengths highlights the importance of applying consistent summary metrics. Also, many countries have passed emission regulation for formaldehyde and more recent measurements/construction are likely to have lower emission rates. As a result, the reported

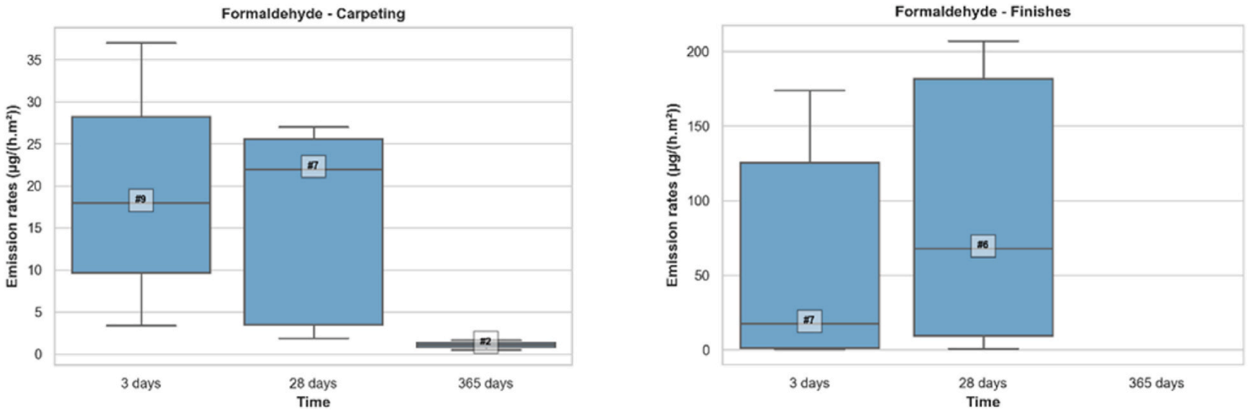

Fig. 11. Statistics of ER of formaldehyde for Carpeting and Finishes after 3, 28 and 365 days – Approach 2.

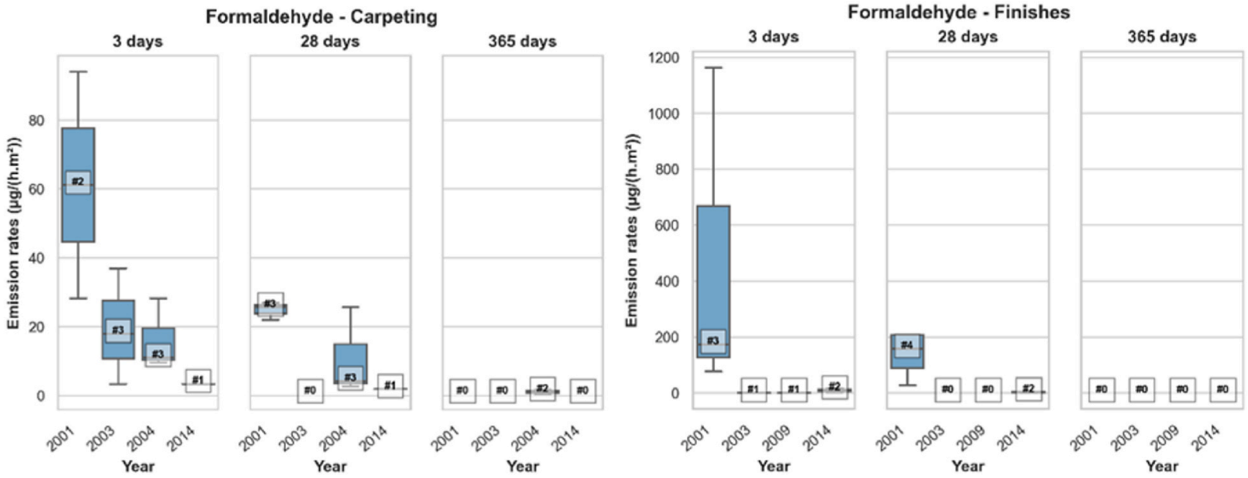

Fig. 12. Statistics of ER of formaldehyde for Carpeting and Finishes after 3, 28 and 365 days, split by years – Approach 2.

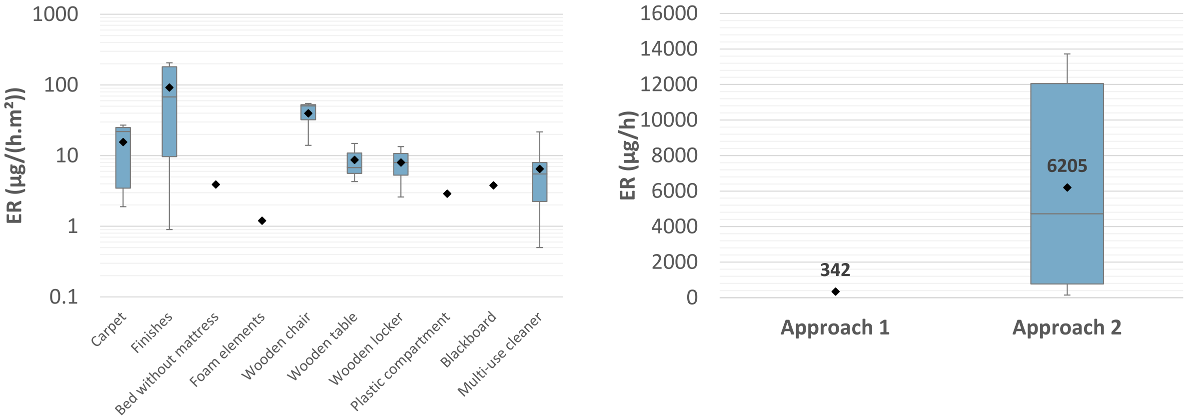

Fig. 13. Statistics of ER for all sources (left) and for the room (right) – Approach 2.

emission rates are likely higher than actual averages reflecting high-emission materials from prior decades, which supports the need to include more recent, regulation-compliant materials. PANDORA is designed to grow over time and easily include and select new data as materials and standards change. Based on our expertise in using this data for IAQ modeling in the frame of Annex86, we recommend using P25 (25th percentile) emission rates (rather than means or medians) to achieve reliable mean concentration levels when

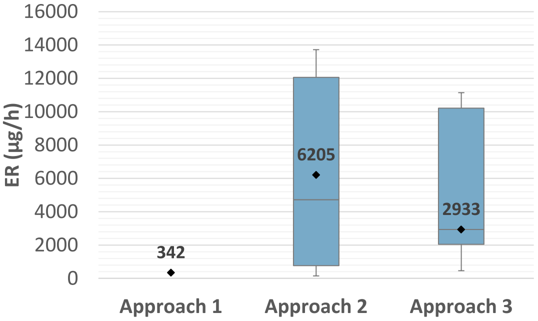

Fig. 14. Comparison of the three approaches in terms of ER for the whole room.

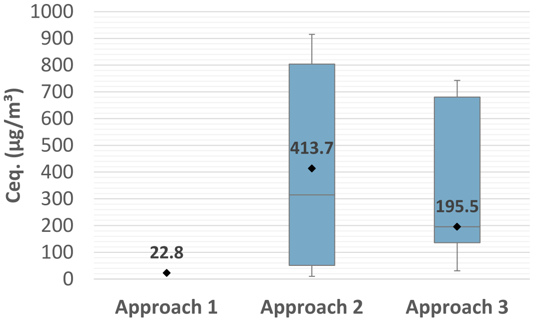

Fig. 15. Comparison of the three approaches in terms of equilibrium concentration that is based on ER after 28 days and is intended to represent long-term concentration.

performing pollutant mass balance calculations in indoor environments. This conclusion only stands for formaldehyde as additional analyses would be necessary for other pollutants.

The results highlight how different data selection approaches can lead to substantial variations in estimated indoor concentrations. Using maximum values (Approach 1) results in conservative estimates that may overstate exposure, while average values can obscure the variability present in real-world data. The percentile-based approach (P25) (Approach 2) reduces the influence of extreme values while still reflecting commonly observed emission levels, giving a wider estimate for modeling purposes, especially when the dataset includes a wide range of emission values. The Metasource approach (Approach 3) relies on aggregated or composite data derived from multiple studies and provides a practical summary when detailed individual records are unavailable. This case study reflects the importance of the use of transparent selection criteria and structured data when estimating pollutant concentrations in indoor environments. It also demonstrates how PANDORA supports consistent modeling decisions by providing access to detailed metadata and comparable records.

5. Discussion

The database currently includes approximately 10,000 emission rates from various indoor sources and pollutants. While the current coverage is extensive, additional data identified in the literature still needs to be incorporated to include the more recent studies. Noteworthy studies have been identified, covering a diverse range of emissions sources, including:

- **Building materials and furnishings**: Emissions from polyester, nylon, and wool carpets [66]; the influence of air renewal on material emissions [67]; the influence of combined effect of temperature and relative humidity on the emission rates [68] and emissions from assembled building materials in walls [69].
- **Consumer products**: VOC emissions from essential oil-based cleaning products ([70,71]), reed diffusers [72] and temperature-dependent VOC emissions from common residential plastic products [73].
- **Office and household equipment**: Emissions of particles from printers using both old and new cartridges [74].
- **Cooking and combustion sources**: VOC emissions from electric stove cooking [75]; ultrafine particle generation from various activities, including candle burning, gas stove usage, clothes drying, tea & toast preparation, broiled fish, and incense burning ([76,77]).
- **Tobacco and alternative smoking products**: PM2.5 generation from electronic cigarettes ([78,79]) and emissions from other combustion sources such as tobacco smoke, mosquito repellent coils, incense, moxa, scented candles, and mosquito repellent electric mats [79].

- **Human emissions**: Ammonia emissions from occupants ([80,81]) and the application of personal care products [82]. Emissions of particulate matter and volatile organic compounds through respiration and skin shedding ([83,84]). Formation of secondary pollutants by skin surface reactions with ozone due to the presence of skin oils containing double carbon bonds [85].
- **Whole-building emissions**: d-limonene, α- and β-pinene, styrene, and formaldehyde emissions at the building scale ([86–88]); VOC emissions from freshly cut Douglas Fir trees [89].

Despite the importance of incorporating these additional data, integrating new records into the database remains a time-intensive process. For reference, adding the last 1000 data points required approximately three months of full-time effort by an IAQ expert already familiar with the database structure. Due to time constraints during the Annex86 project, integrating these newly identified datasets has not yet begun. This underscores the urgent need for more efficient solutions, particularly the development of user-friendly automated data curation tools accessible to a broader range of researchers. While current methods, often relying on programming languages like Python, offer powerful automation, they can present a significant barrier for researchers without extensive coding literacy. By minimizing manual intervention and democratizing the curation process through intuitive interfaces, these automated tools can significantly reduce the time and effort required for data integration, improve data quality and consistency, and accelerate the growth of comprehensive indoor environmental databases.

The efforts to calculate summary statistics were made to simplify data usage. However, even for formaldehyde, which has the largest number of emissions recorded, the data are often insufficient to be statistically representative of the wide variation in real-world sources. Additionally, the selection of sources for evaluation is somewhat biased, as priority has generally been given to potentially high-emission sources at least for pioneer works and not with the objective of being representative of the category of sources investigated. As a result, the reported emission rates are likely higher than actual averages. This has been especially observed for formaldehyde in construction and decoration materials, where most data relate to materials that were produced and used in buildings before regulations were introduced to limit these sources of pollutants indoors. Based on our expertise in using this data for IAQ modeling, we recommend using P25 emission rates for formaldehyde (rather than averages or medians) to achieve realistic average concentration levels when performing pollutant mass balance calculations in indoor environments.

To further simplify data use, initial efforts in meta-data calculations have focused on aggregating all emission data into a single dataset, without distinguishing between the typical application of construction or decorative materials to specific surfaces such as floors, ceilings, or vertical walls. A more refined approach would account for the intended use of materials by assigning probability distributions to different surfaces. However, implementing such a system would require an additional database field to specify the likelihood of a material being applied to a particular surface. This enhancement is planned for future database development.

Where possible, it is best to use available emission data directly for the materials used, or to refer to labeled products. The reality is that many building products are becoming available at a rapid rate. The evaluation of these products for emissions is lagging. For activities, this information is even more scattered. Despite its limitations in terms of data representativeness, the PANDORA database therefore represents an important library to consider the impact of indoor sources, materials and activities that are otherwise not considered in the quest for buildings that provide good indoor air quality.

6. Conclusion

This paper presents the recent advancements in the development of PANDORA, a database for indoor pollutant sources. The major feature of PANDORA is its ability to compile both gaseous and particulate sources in a single database, providing emission rates essential for modeling room concentration levels, along with additional relevant information for IAQ studies.

Currently, PANDORA contains a vast amount of data, including 9968 emission rates from individual indoor sources. However, even for the category with the most data, i.e. construction and decoration materials, it is still not statistically representative of current indoor sources and is biased towards (very) high emission rates from the oldest investigated sources. As new data, such as those identified in this study, are integrated, the statistical analyses and metadata presented here will increasingly offer a more reliable representation of source strengths for IAQ assessments. Users should apply emission rates cautiously, considering regional variations and context-specific factors not fully captured by the database.

Looking ahead, additional filters, such as publication year and country, will be necessary to enhance the ease of searching for specific emission rates within PANDORA. Furthermore, a procedure should be established that enables researchers to contribute new data to the database and preformat it for inclusion, which will help streamline this process.

We hope the database will play a role in the quest to design healthy buildings, for which IAQ is an important consideration. When no alternative data is available, the database may serve as an easily accessible source of information to define inputs for calculation as needed in Technical Standards. Manufacturers may also find the database an important reference for innovations they are considering.

CRediT authorship contribution statement

Marc Abadie: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eol Geffre:** Software, Investigation, Data curation. **Charles-Florian Picard:** Software, Methodology, Investigation, Data curation. **Marcel Loomans:** Writing – review & editing, Writing – original draft, Investigation. **Francesco Babich:** Writing – original draft, Investigation. **Aurora Monge-Barrio:** Writing – original draft, Investigation. **Dusan Licina:** Writing – original draft, Investigation. **Gráinne McGill:** Writing – original draft, Investigation. **Linda Toledo:** Writing – original draft, Investigation, Writing – review & editing. **Ann Marie Coggins:** Writing – original draft, Investigation.

Mohsen Pourkiaei: Writing – original draft, Investigation. **Núria Casquero-Modrego:** Writing – review & editing, Writing – original draft, Investigation. **Constanza Molina:** Writing – review & editing, Writing – original draft, Investigation. **Sasan Sadrizadeh:** Writing – original draft, Investigation. **James McGrath:** Writing – original draft, Investigation. **Gabriel Rojas-Kopeinig:** Writing – original draft, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.114216.

Data availability

All data in the PANDORA database are fully accessible and clearly referenced, allowing users to trace each entry back to the original published studies for verification and further exploration.

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