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Indoor exposure to ultrafine particles related to domestic activities: A systematic review and meta-analysis

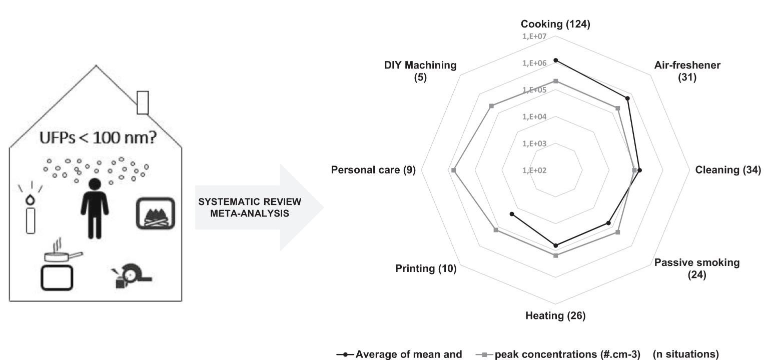
Sabyne Audignon-Durand[a,b,*], Olivier Ramalho[c], Corinne Mandin[c], Audrey Roudil[b], Olivier Le Bihan[d], Fleur Delva[a,b], Aude Lacourt[a]

[a] *University of Bordeaux, INSERM, BPH, UMR1219, EPICENE Team, Bordeaux 33000, France*
[b] *Bordeaux University Hospital, Environmental and Occupational Health Department, Bordeaux 33000, France*
[c] *Scientific and Technical Center for Building, Marne-La-Vallée 77447, France*
[d] *Air Breizh, Association for Ambient Air Quality, Rennes 35 200, France*

HIGHLIGHTS

- A comprehensive analysis of indoor exposure to UFPs as part of domestic activities was carried out.
- 69 studies from highly industrialised countries were included leading to the analysis of 346 exposure situations.
- 9 main groups of activities involving >50 different emission processes were identified.
- According to the meta-analysis, grilling food and using a hair dryer lead to the highest levels of exposure.
- These results contribute to a more accurate assessment of domestic exposure to UFPs.

GRAPHICAL ABSTRACT



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ABSTRACT

Ultrafine particles (< 100 nm) are of increasing concern because of their toxicological potential. Emission processes suggest their presence in all environments, including at home, where particularly at-risk populations may be exposed. However, knowledge of their impact on health is still limited, due to difficulties in properly assessing exposure in epidemiological studies.

In this context, the objective of this study was to provide a complete summary of indoor exposure to ultrafine particles in highly industrialised countries by examining the domestic activities that influence such exposure.

We conducted a systematic review, according to PRISMA guidelines using PubMed, Web of Science and Scopus up to and including 2021. We carried out a qualitative and quantitative analysis of the selected studies with a standardised template. Exposure circumstances, measurement methods, and results were analysed. Finally, a meta-analysis of the measured concentrations was performed to study exposure levels during domestic activities.

The review included 69 studies resulting in the analysis of 346 exposure situations. Nine main groups of activities were identified: cooking, which was the most studied, smoking, the use of air-fresheners, cleaning, heating, personal care, printing, do-it-yourself activities, and others. Over 50 different processes were involved in these activities. Based on available particle number concentrations, the highest average of mean concentrations

* Corresponding author at: University of Bordeaux, INSERM, BPH, UMR1219, EPICENE Team, Bordeaux 33000, France.
E-mail address: sabyne.audignon@u-bordeaux.fr (S. Audignon-Durand).

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was associated with grilling (14,400 × 10^3 cm^{-3}), and the lowest with wood stove (18 × 10^3 cm^{-3}). The highest average of peak concentrations was that for the use of hair dryers (695 × 10^3 cm^{-3}), and the lowest for the use of air cleaners (11 × 10^3 cm^{-3}).

A hierarchy of domestic activities and related processes leading to ultrafine particle exposure is provided, along with average exposure concentrations at home. However, more extensive measurement campaigns are needed under real-life conditions to improve assessments of indoor exposure to ultrafine particles.

1. Introduction

Improving indoor air quality is a crucial public health issue and became even more important during the Covid-19 pandemic, during which repeated lockdowns inside the home were imposed (Zhang et al., 2022). Apart from such specific situations, certain groups of people who are particularly vulnerable, such as pregnant women, young children, and the elderly, spend most of their time at home in industrialised countries (Kelly and Fussell, 2019). The World Health Organization (WHO) estimated that, in Europe, 117,000 deaths from among the main non-communicable diseases (i.e., ischaemic heart disease, stroke, lung cancer, and chronic obstructive pulmonary disease) were associated with indoor air pollution in 2012 (WHO and Regional Office for Europe, 2019). Among air pollutants, nanoparticles (<100 nm) have raised many questions over the last 20 years due to the increase in their production and their use in a large number of sectors, e.g., agri-food, construction, medical, and electronics (Barhoum et al., 2022). Some nanoparticles are also emitted unintentionally from natural sources, erosion, forest fires, and volcanic eruptions, and from anthropological sources, through fossil fuel combustion and machining processes, for example (Manigrasso et al., 2019). Given these different origins, the term "engineered nanoparticles" (NPs) is commonly used for nanoparticles intentionally manufactured for commercial purposes, while the term "ultrafine particles" (UFPs) is used for those unintentionally emitted into outdoor and indoor air. Indoors, UFPs may be derived from outdoor air and are directly emitted by domestic activities, such as cooking or wood burning. Both UFPs and NPs share high surface reactivity, one of the well-known determinants of nanoparticle toxicity, causing high biological reactivity (Bakand and Hayes, 2016). Indeed, several toxicological studies have highlighted their adverse effects on cells and tissues, such as oxidative stress, genotoxicity, inflammation, and fibrosis (Avogbe et al., 2005; Stone et al., 2007). Moreover, their ability to cross biological barriers raises questions about possible damage to organs (the lungs), to the central nervous system (the blood-brain barrier), or during foetal development (placental barrier) (Elder and Oberdorster, 2006). In recent years, epidemiological studies on outdoor air pollution have shown that exposure to UFPs plays a role in the occurrence of cardiovascular diseases, respiratory diseases, and cancer (Schraufnagel, 2020). However, most of these studies were based on methods to assess exposure that were often not comparable or not specific to UFPs (Ohlwein et al., 2019; Samoli et al., 2020). One reason was the method used to measure the UFPs. For these very small particles, mass measurement is no longer appropriate and other parameters must be monitored, such as the surface area and number of particles (Maier et al., 2008). The chemical composition of UFPs and their morphology are also important parameters, as they can influence their toxicity by modifying the surface reactivity, by conferring high bio-persistence, or by the presence of adsorbed chemicals on the particle surface (Stone et al., 2017). In addition, UFPs are typically found alongside larger particles to form an unstable and polydispersed aerosol (Buseck and Adachi, 2007). The particle-size distribution should also be monitored to provide the proportion of UFPs. To date, it is necessary to use a combination of real-time measuring devices and filter sampling for offline analysis (Witschger, 2011). The lack of a harmonized method to measure UFPs has led to measurement campaigns using different methods, producing heterogeneous exposure data. This has been relatively well demonstrated for the workplace (Viitanen et al., 2017). In non-occupational settings, a comprehensive study on the state of available exposure data is lacking and would complement existing non-exhaustive reviews (Ali et al., 2020; Chen et al., 2021; Marval and Tronville, 2022; Morawska et al., 2017; Nazaroff, 2023). Moreover, the activities of home occupants have been shown to influence indoor air quality and a specific knowledge of these activities is, therefore, essential for the accurate assessment of exposure to UFPs in the indoor environment (Baeza Romero et al., 2022; Koivisto et al., 2019).

In this context, the objective of this review was to carry out a comprehensive and updated analysis of available exposure data on UFPs with respect to indoor domestic activities.

2. Methods

We performed a systematic literature review based on the PRISMA guidelines. The protocol was registered on PROSPERO (ID: CRD42022341214) (Moher et al., 2009). The search strategy was designed to collect and analyse all UFP exposure data related to indoor domestic activities until January 1, 2022. PubMed, the Web of Science, and Scopus were queried using the following search algorithm: ((ultrafine OR nanoparticle* OR nanoscale OR "PM1") AND (indoor OR residen* OR domestic OR home* OR dwelling* OR house*) AND (exposure OR measure*) NOT (occupational OR workplace*)) AND (English [language] OR French [language])). There was no restriction for the date of publication. Endnote® was used to manage the references and exclude duplicates.

The study selection process was based on an initial screening of the title and abstract, followed by reading of the full text according to the following eligibility criteria. Original and interventional studies were included, whereas letters and reviews were excluded, as well as in-vitro and animal studies. We restricted the inclusion to the most highly industrialised countries with comparable lifestyles, i.e., European countries, the USA, Canada, Japan, Australia, and New Zealand (United Nations, 2022). Studies with conditions that were not representative of direct or realistic exposure to a domestic activity were not selected. Studies performed in experimental houses, chambers, or rooms simulating residential activities were considered if they had a minimum volume of 15 m^3. Indoor situations in the workplace, transport, and public buildings were not considered, nor were studies dealing with infiltration or penetration of outdoor pollution. The domestic activities had to be clearly identified and well described (used process at least). Measurement had to be performed during the activity and results given by activity. The method and strategy used had to be described. Moreover, measurement results had to be usable without further interpretation. Thus, no data was extracted from temporal series or graphs. Study selection was performed according to the particle size ranges measurable with the devices used. Only studies that included the UFP size fraction (i.e., < 100 nm) were included. Results expressed as mass (PM0.1 and PM1) and emission rates (number of particles per minute or second) were excluded.

We conducted a qualitative and quantitative analysis of the selected studies according to a standardised analytical template (see Table A1). The qualitative analysis focused on a description of the situation of exposure and the methods of measurement. The exposure situations identified in each study corresponded to the different conditions for performing an activity. We analysed all descriptive information for the situation, including the activity, the process used, in particular, its principle of operation, the energy and materials involved, the duration of the activity, and the people carrying out the activity or present in the room. The location of the activity was studied, including the dimensions and layout of the room, ventilation, heating, and outdoor environment (traffic and geographical location). The methods of measurement were also analysed, including the use of real-time instruments, media sampling, and physical and chemical analysis. Particular attention was paid to the characteristics of the instruments, such as the operating principle and limits of detection and quantification. The sampling strategy was also studied regarding the number and duration of measurements and the position of the instruments within the breathing zone (individual), at a fixed point close to the activity (ambient), or at a distance to distinguish the reference aerosol (background or BKG). Quantitative variables were extracted from the measurement results: particle number concentration (PNC), surface area concentration (SAC), particle size distribution (PSD), chemical composition, and morphology. From this analysis, the qualitative and quantitative variables were recorded in an Excel® database. In addition, a meta-analysis of PNC results was performed to provide a concentration of exposure according to the available statistical data and descriptive variables defined in Table 1. The mean and peak PNC values were used as reported in the original studies without data processing. The different particle size ranges of the measurement devices used were not taken into account in the analysis. The averages of the mean and peak concentrations were then calculated per activity and process if at least two results were reported. A mean value was calculated from the minimum and maximum values if no mean was provided.

Finally, the quality of each study was assessed in terms of its contribution to understanding and quantifying indoor domestic exposure to UFPs. Ranking was based on the availability of information on the situation, the measurement method, and the type of metrics. Each of these three variables was rated between 0 and 2 according to the ranking rules in Table 2. For the situation and the measurement method, a value of 0 was assigned if they were poorly described, 1 if partial information was indicated, and 2 if sufficient information was provided. For the type of metrics, a value of 0 was assigned if only the concentration or size distribution was reported, 1 if the concentration and size distribution or concentration and physical-chemical characteristics were reported, and 2 if all metrics were provided. The scores for each of the three variables (situation, measurement method and type of metrics) were summed to obtain a final score on a scale from 0 to 6, corresponding to the relevance of each study to document indoor exposure to UFPs: low (score ≤ 2), medium (3 or 4), or high (score ≥ 5) relevance. The publication analysis and their ranking were independently performed by two reviewers (authors SA and AL). Discrepancies were discussed in a meeting to reach a consensus.

3. Results

3.1. Study selection

From the bibliographical database, 9419 results matched the search query (see Fig. 1). After the removal of duplicates, 5413 references were screened by title and abstract leading to the selection of 385 studies for eligibility assessment. Based on reading of the full text, 316 studies were excluded in compliance with the ineligibility criteria. Finally, 69 original studies were included in the analysis (see Table A2). Ranking of the studies showed 27 to be of high interest to document UFP exposure, 39 of medium interest, and three of low interest. In total, 56 studies were considered to provide sufficient information on the situation and 46 on the method of measurement. The documentation of the metrics was the

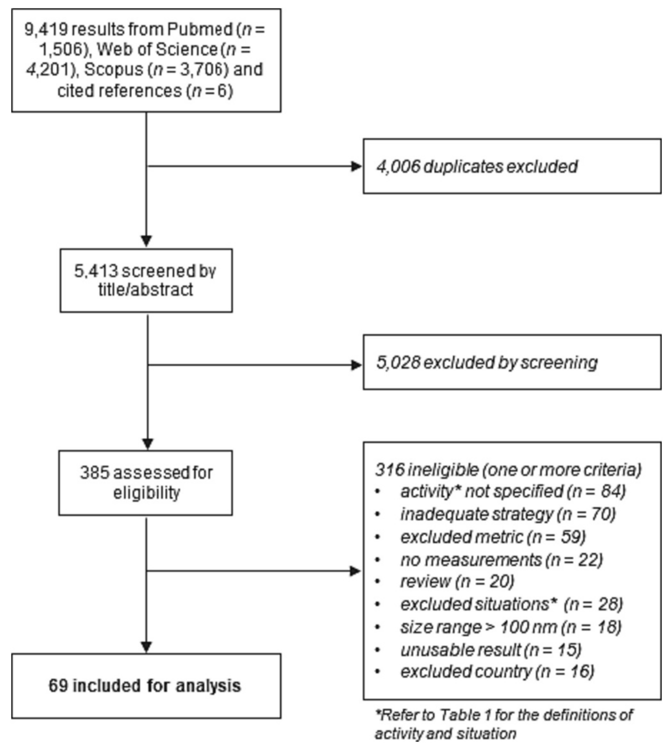

Fig. 1. Flow chart of the selection process in the systematic review.

Table 1
Definition of descriptive variables used in the meta-analysis.

Variable	Definition
Situation	Refers to a context (i.e., the circumstances) in which an activity involving a given process is performed
Activity	The general category for a residential task (e.g., cooking, cleaning, etc.)
Process	A more precise description of the activity including details of the technical device or equipment used by the occupant (e.g., for heating: wood stove, electric heater, etc.)
Mode	Used instead of process for cooking (e.g., frying, grilling, baking, etc.)

Table 2
Rules for ranking studies to assess their relevance for indoor exposure assessment.

Variable	Rating criteria		
	0	1	2
Situation	Activity, process	Activity, process and details on process (e.g., materials, energy, principle of operation) or details on the room and/or dwelling (e.g., volume, ventilation)	Activity, process and details on process and room and/or dwelling
Measurement method	Measuring devices	Measuring devices (name and characteristics) and location of the measurement	Measuring devices and full strategy described (number, duration, location, resolution time, background)
Available metrics	Concentration or size distribution	Concentration and size distribution or concentration and physical/chemical characteristics	Concentration and size distribution and physical/ chemical characteristics

most penalizing item. Among the 69 studies, 28 had the lowest level of information: 21 presented only a number concentration, one both a number concentration and a surface concentration, and six only a size distribution. Only four studies provided all metrics and had the maximum score to document indoor exposure to UFPs (score = 6). No study was excluded due to the ranking results, as the inclusion/exclusion criteria were already highly selective.

3.2. Study designs, activities, and measurement methods

The oldest study was published in 2000 and two thirds of the studies were published in the 2010s ($n = 44$) and mainly in European and North American countries, with the USA ($n = 16$) first and then Italy ($n = 15$). Most studies were conducted under experimental conditions ($n = 42$), including seven in experimental houses. In compliance with the selection criteria, the experimental conditions were representative of realistic exposure. The field studies ($n = 27$) were conducted in houses ($n = 20$), flats ($n = 8$), and a university residence (n = 1). Fourteen studies investigated more than one dwelling (from 2 to 40) and for three, the results were given as the mean for all dwellings.

In total, 346 different exposure situations were analysed across the 69 studies. Eight major groups of activities were identified: cooking, passive smoking, the use of air-fresheners, cleaning, heating, personal care, printing, and do-it-yourself (DIY) (see Table 3). The activities were then detailed according to the process used; nearly 50 different processes were identified (see Table A3). Processes were classified by activity according to their use rather than the technology employed. “Spray” processes were, therefore, found in several categories. The category “other activity” was created to group processes that could not be classified in the main groups of activity, such as the use of Bengal fires and matches. Cooking was by far the most frequently documented activity, whereas DIY and printing were the least documented activities.

The particle number concentration (PNC) was by far the most often measured metric and was provided for all situations, except for the group of other activities. Except for heating and cleaning, information about the particle size distribution (PSD) was available for all activities and for at least half of the situations. Surface area concentration (SAC) and physical-chemical characteristics were poorly documented.

The most frequently used real-time devices were scanning mobility particle sizers (SMPSs) and condensation particle counter (CPCs), used in 31 and 23 studies, respectively. SMPSs measure the particle size distribution by combining an electric mobility particle sizer with an individual particle counter to deliver particle concentrations in size channels. By summing over the size channels, a total concentration can be obtained. For the SMPSs used in the selected studies, particle size ranged from 2 nm to 1 μm. CPCs do not distinguish particles by size, instead providing a single particle number concentration for a size range that varies from one device to another, mostly from 10 nm to 1 μm (see Table A2 for information on each measuring device). The strategy used in all studies was to measure exposure at a fixed point in the studied space. Only one study with personal measurements was retrieved. However, the results provided for cooking activity were expressed as the average for all 40 participants (Shehab et al., 2021). In addition, in four studies, some measurements were performed at a point representing the breathing zone of a person performing the targeted activity (cooking, use of air-fresheners, cleaning, personal care, printing, or DIY) (Manigrasso et al., 2017; Vu et al., 2017; Zhang et al., 2010; Zontek et al., 2017). Background particle metrics were measured in 57 studies, either just before the start of the activity or by deduction from the periods without activity.

3.3. Exposure concentrations by activity and related process

Fig. 2 shows the distribution of the mean concentrations reported by the authors for the studies retained, by domestic activity (see Table A4 for the descriptive statistics used). The calculated averages of the mean and peak concentrations are reported in Table 4, by activity and process (see Table B1 for a complete list of the raw data used in the meta-analysis, i.e. mean and peak concentrations, and a description of the corresponding situations including activities, processes and cooking modes).

Based on the average of mean concentrations, cooking, air freshener use (particularly those involving burning) and cleaning resulted in the highest levels of exposure, above 10^5 cm^{-3}, whereas passive smoking, heating and printing resulted in the lowest levels of exposure. A wide range of mean concentrations was observed for each activity, except cleaning, based on the first and third quartiles. Each average of mean concentrations exceeded the mean urban background concentration estimated at about 10,000 cm^{-3} (Morawska et al., 2008).

Cooking led to the highest average of mean concentrations, at $>10^6$ cm^{-3}. The highest concentrations were reported when grilling, toasting bread, and cooking a meal or breakfast under real-life conditions or in experimental houses. Other modes had average means on the order of 10^5 cm^{-3}. The highest peak concentration was measured while frying in oil on an electric stove for 15 min (Ciuzas et al., 2015), whereas no increase above the background concentration was detected during the cooking of scrambled eggs (reported as a zero-value peak) (Wallace and Ott, 2011). Information about particle size was available for all cooking modes, and the particle size for the main mode was predominantly on the ultrafine scale (Buonanno et al., 2011; Buonanno et al., 2009; Dennekamp et al., 2001; Fromme, 2019; Glytsos et al., 2010; He et al., 2004; Manigrasso et al., 2015; Manigrasso et al., 2017; Vu et al., 2017; Wallace et al., 2008; Wierzbicka et al., 2015).

The use of air-fresheners was the activity that resulted in the second highest level of exposure to UFPs after smoking and cooking. This was particularly due to the burning of candles (scented or unscented) as half of the measurements exceeding 10^6 cm^{-3} in situations involving several candles. PSD measurements showed 85 % of the particles to be 50 nm at the beginning of the burning of the candle, after which the percentage of UFPs decreased and a second mode > 100 nm emerged (Glytsos et al., 2010). The highest peak concentration was measured in the breathing zone 1.5 m from an incense cone (Manigrasso et al., 2017). The percentage of UFPs decreased from 45 to 20 % during the burning of incense (Glytsos et al., 2010). Overall, the size mode ranged from 100 to

Table 3
Numbers of situations and available metrics retrieved by activity.

Activity (*n* studies)[a]	# situations[a]	Number concentration	Surface concentration	Size distribution	Chemistry or morphology
Cooking (30)	170	163	37	93	2
Air-freshener (20)	40	36	10	29	2
Cleaning (19)	39	35	1	18	0
Passive smoking (18)	30	24	2	13	0
Heating (9)	29	28	3	3	0
Personal care (7)	14	11	3	7	0
Printing (6)	13	11	0	6	5
Do it yourself (3)	10	10	1	6	0
Other activity (1)	2	0	0	2	1

[a] More than one activity could be investigated in the same study, and more than one metric could be measured for each situation.

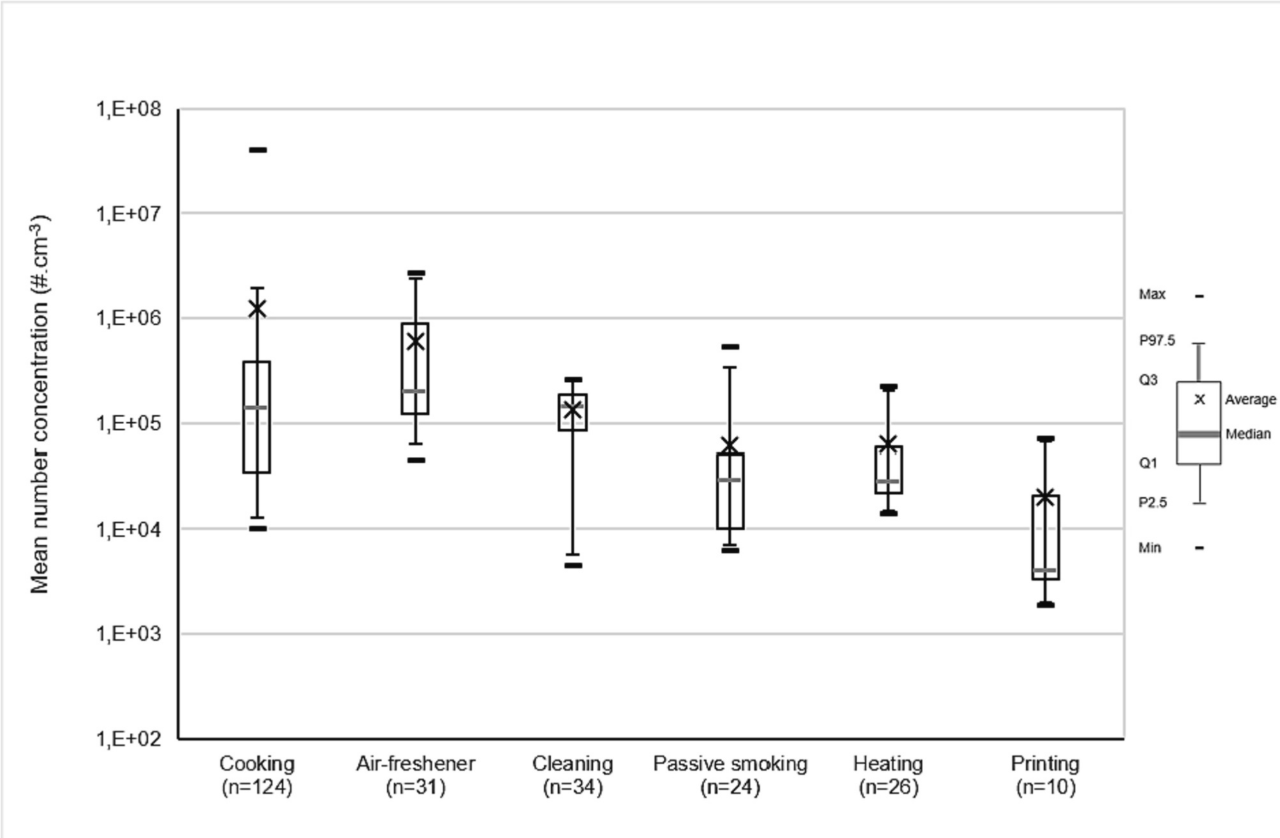

Fig. 2. Distribution of the mean concentrations reported, by activity (*n* situations).

186 nm (Glytsos et al., 2010; Ji et al., 2010; Manigrasso et al., 2017; Manoukian et al., 2013; Vu et al., 2017). For non-combustible air fresheners, the reported peaks were much lower (close to 10^4 cm^{-3}) for sprays than for candles or incense.

Cleaning corresponded to an average mean of slightly above 10^5 cm^{-3}. Vacuum cleaner use was the most investigated cleaning process, for which a wide range of means was obtained with two orders of magnitude between the minimum and maximum values. The highest mean concentration was measured during a test involving a cylinder wet vacuum cleaner and the lowest mean corresponded to the use of a HEPA filter-equipped robot vacuum cleaner (Vicente et al., 2020). For ironing, a large range of peaks was observed due to different uses. However, steam ironing corresponded to the highest values (mean, peak), in contrast to ironing without steam (lowest peak) (Ciuzas et al., 2015; Vicente et al., 2021; Wallace et al., 2011). During the handling of cleaning products, the highest peak was measured under real-life conditions when using a cleaning spray in the living room of a house (Wallace and Ott, 2011). For all activities and processes, the lowest average of peak concentrations was obtained for air cleaners regardless of the technology used (non-thermal plasma, ozone, or ion generators). Peak values were similar for plasma and ozone generators: 2.0 and 2.3 × 10^4 cm^{-3} in the summer and 3.5 and 5 × 10^3 cm^{-3} in autumn (Ardkapan et al., 2011). For ionizers, a peak value of 10^3 cm^{-3} was measured regardless of the season. The PSD was available only for ion generators, with a size range from approximately 4 to 150 nm (Siegel et al., 2006; Waring et al., 2008).

For passive smoking, higher mean and peak concentrations were measured for cigarettes than for e-cigarettes (Manigrasso et al., 2017; Nasir and Colbeck, 2013; Schober et al., 2014; Scungio et al., 2018). However, far fewer means were reported for cigarettes, (3 values) than for e-cigarettes (17 values) in the studies selected, and the same was true for peak concentrations. The mode of particle size was lower for e-cigarettes than for cigarettes, at about 30 nm and 100 nm, respectively (Avino et al., 2018; Glytsos et al., 2010; Palmisani et al., 2019; Schober et al., 2014).

Heating was among the least activities resulting in the lowest exposure to UFPs, based on the average of mean concentrations. Wood heating was the most documented heating process. Fireplaces were associated with a high average of mean concentrations, i.e., 68.5 × 10^3 cm^{-3} for closed fireplaces and 128 × 10^3 cm^{-3} for open fireplaces, respectively, whereas wood stoves gave a much lower average mean of 18 × 10^3 cm^{-3}. However, wood stoves led to much higher peaks of exposure mainly due to the opening of the door, whereas the concentration in the room decreased as the burning continued (Salthammer et al., 2014). Particle size was documented only for fireplaces, for which the mode was under 100 nm (Hussein et al., 2005; Zhao et al., 2020). For electric heaters, a wide range of peaks was observed for different technologies. The highest peak was reached for an air-blowing heater and the lowest for an oil-filled heater (Ciuzas et al., 2015).

Personal care led to a much higher average peak than other activities, mostly due to the use of hair dryers, which yielded the highest peak for all processes (Ciuzas et al., 2015). By comparison, the mean PNC measured in the breathing zone when drying hair was lower, ranging from 5.3 × 10^4 to 2.5 × 10^5 cm^{-3} (Manigrasso et al., 2017). Mode particle sizes of approximately 10 and 25 nm were measured for hair dryers (Manigrasso et al., 2017). Only peak concentrations were reported for hair irons. A peak of 9 × 10^5 cm^{-3} was measured in a simulated breathing zone (Manigrasso et al., 2017) and peaks from 1.27 to 3.24 × 10^5 cm^{-3} at a fixed point in a bathroom (Wallace and Ott, 2011).

Printing was the activity associated with the lowest level of exposure to UFPs, with an average of mean concentration close to 10^4 cm^{-3} corresponding exclusively to plastic 3D printing, an increasingly popular leisure activity. 3D printers are usually fed with two types of filaments:

Table 4
Mean and peak of particle number concentrations by activity and process.

Activity, process	# situations[a]	Mean concentration (10^3 cm^{-3})		Peak concentration (10^3 cm^{-3})	
		Average	Range	Average	Range
Cooking	124	1240	10 to 41,000	210	0[b] to 2210
Frying	39	169	10 to 607	268	3.4 to 2210
Grilling	25	14,400	210 to 41,000	206	0.1 to 1180
Oven baking	16	115	35 to 270	118	16 to 410
Boiling	17	186	13 to 356	125	1 to 573
Toasting	6	854	100 to 1550	195	114 to 396
Stir-frying	6	357	20 to 900	84	11 to 137
Pan-cooking	8	253	20 to 800	73	0[b] to 192
Several modes	7	583	13 to 1200	856	5 to 1800
Air-freshener	31	607	46 to 2670	185	4 to 890
Burnt	29	607	46 to 2670	205	26 to 890
Candles (scented or otherwise)	17	975	110 to 2670	272	49 to 890
Incense	12	135	46 to 225	83	26 to 170
Spray	2	/	/	17	4 to 30
Cleaning	34	134	5 to 260	85	1 to 440
Vacuum cleaner	13	81	5 to 169	56	5 to 210
Products handled	8	/	/	107	2 to 330
Iron	8	223	170 to 260	145	1 to 440
Air cleaner	5	/	/	11	1 to 23
Passive smoking	24	61	6 to 540	187	24 to 668
Cigarette	9	223	13 to 540	193	29 to 668
E-cigarette	15	32	6 to 85	181	24 to 284
Heating	26	64	14 to 226	152	1 to 988
Wood heater	20	64	14 to 226	163	3 to 988
Wood stove	16	18	14 to 22	163	3 to 988
Fireplace	4	87[c]	24 to 226	/	/
Electric heater	6	/	/	124	1 to 485
Personal care	9	/	/	634	2 to 4010
Hair dryer	7	/	/	695	2 to 4010
Hair iron	2	/	/	450	127 to 900
Printing	10	20	2 to 72	142	3 to 962
Paper laser printer	6	/	/	142	3 to 962
3D plastic printer	4	20	2 to 72	/	/
DIY Machining	5	/	/	242	21 to 701

" / " no concentration or only one concentration was reported; concentrations exceeding the upper limit of measuring devices (generally 10^6 cm^{-3}) represent <5 % of the total number of concentrations.
[a] Number of situations for which a measurement result was used.
[b] Not detected over the background.
[c] Calculated for three values.

acrylonitrile butadiene styrene (ABS) and poly-lactic acid (PLA). This printing process corresponded to one of the lowest means reported. For indoor air, a 4 h printing operation using ABS resulted in a mean concentration of 7.2×10^4 cm^{-3} (Gu et al., 2019). In the breathing zone, the PNC means ranged from 1.86 to 3.78×10^3 cm^{-3} using ABS and did not exceed 4×10^3 cm^{-3} using PLA during a 60-min printing operation (2 different brands) (Zontek et al., 2017). Size modes were reported for ABS printing only, ranging from 2.1 to 9.4 nm. Apart from 3D printing, laser printing was the only one of the widely used paper-printing technologies documented in the selected studies. Laser printing on paper reached one of the highest peak concentrations for measurement in front of the printer, but exposure decreased with distance from the printer to reach the lowest peak recorded at a distance of 2 m (Wang et al., 2011). In the same study, PSD showed a peak of particles of 30 nm at the beginning, with particles of larger size emitted as more pages were printed. In a home office (30 m^3), the laser printing of 10 pages led to peaks ranging from 0.6 to 1.9×10^4 cm^{-3} (Wallace and Ott, 2011). Home offices have become increasingly common, but these peaks were among the lowest reported.

For DIY, only peak concentrations were reported and were related to machining operations (without material, lasting 4 min) (Wallace et al., 2011b). The measured peaks showed the highest average of peaks for sawing (3.37×10^5 cm^{-3}), followed by sanding (1.61×10^5 cm^{-3}) and drilling (3.85×10^4 cm^{-3}).

No average could be calculated for mean or peak concentrations for the following processes, for each of which only one result was available: the use of a microwave, gas clothes dryer, electrical diffuser, mosquito coil, forced gas air boiler, hair spray, shaver, inkjet printer, and some DIY tools (compressor, pump, and spray can).

4. Discussion

This review provides state-of-the-art data on exposure to UFPs in indoor air associated with domestic activities. The main activities and processes were identified and the associated concentrations were reported. Cooking was found to be the activity associated with the highest levels exposure according to the average of mean concentrations, whereas personal care led to the worst-case exposure situation, due to the use of hair dryers, with a peak concentration close to 10^6 cm^{-3}.

4.1. Sensitivity analysis

We assessed the influence of the chosen statistical parameter on the ranking of the activity for exposure to UFPs, using the median, rather than the averages of mean concentrations (see Fig. 2). The activity groups with the highest and lowest levels of exposure were unchanged. Activities associated with high levels of exposure had median values clustering close to and above 10^5 cm^{-3}. For peak concentration (see Fig. S1 and Table A6), the use of median values did not change the activity with the highest peak (personal care) but did modify that with the lowest peak (printing instead of cleaning).

4.2. Limitations

These results contribute to our knowledge of the sources of exposure to UFPs within homes. However, the list of sources used is not exhaustive and could be enriched. Inconsistencies were observed in the results of the meta-analysis, with average peak values below the average mean, and a large range of values for the same activity and process. Indeed, data were aggregated from several studies with different measurement methods and diverse circumstances, resulting in considerable variability between the situations analysed (e.g., characteristics of the process, ventilation, room layout, etc.). In particular, ventilation and air exchange conditions, and room volume, are parameters with a major effect on particle concentrations. When available, they are reported, together with other descriptive information, in Tables A2 and B1. Moreover, the background concentration was not systematically provided in the studies and could not therefore be subtracted from the values obtained. The outdoor environment may therefore have contributed to heterogeneity in the concentrations of particle indoors. Table A2 reports whether the average or the peak concentrations was already corrected against the background. These differences between studies must be considered in the interpretation of the results of the meta-analysis. Mean concentration was the statistical parameter used in the meta-analysis, as this was the parameter most frequently reported in the selected studies. Indoor aerosols are relatively unstable, and their particle concentrations do not typically follow a normal distribution (Ramachandran and Cooper, 2011). Median values would therefore have been more relevant than means, but, unfortunately, were not systematically reported in the selected studies and could not, therefore, be used. In addition, we were unable to take into account the number and duration of measurements for the calculation of the average, as they were not systematically provided. Finally, the UFP measurement devices covered different particle size ranges, e.g., starting at 2, 5, 10 or 20 nm, and some including particles >100 nm (up to 1 μm). These differences in diameter ranges were not taken into account in our meta-analysis due to considerable heterogeneity of the devices used. Only particle number concentration was used to document the exposure level in the meta-analysis, because too few data were available for surface area. This is not specific to the indoor domestic environment and the situation is similar for the workplace (Audignon-Durand et al., 2021). Nevertheless, the surface area is still the most appropriate metric according to the concept of nanotoxicology. Higher biological reactivity has been demonstrated for nanometre- than micrometre-sized particles of identical chemical composition at an equivalent mass concentration, expressed by an increase in the specific surface area closely related to the number of particles (Maier et al., 2008). For example, in terms of both particle number and surface area, passive smoking leads to lower levels of exposure to UFPs for e-cigarettes than for cigarettes (Scungio et al., 2018). For active smoking, the number concentrations measured in the mainstream aerosol are higher for e-cigarettes than cigarettes, whereas surface area concentrations are lower for e-cigarettes than for cigarettes. Furthermore, using these surface area concentrations in an excess lifetime cancer risk model (ELCR), the ELCR is lower for e-cigarettes than for cigarettes for both active and passive smoking (Scungio et al., 2018). Similarly, too few results were available concerning the physical/chemical characteristics of the emitted UFPs to be discussed. This would, however, help in understanding the origin of the emitted particles and allow consideration of toxicity parameters other than number and size (e.g., shape or chemical composition). All of these limitations are mainly due to the lack of homogeneity in the measurements performed and in the information provided.

4.3. Contribution

One of the strengths of our study is that we used specific criteria to select realistic indoor domestic exposure situations. By contrast, most existing reviews on indoor UFPs have included experimental studies in chambers of small volume (e.g., a few m^3) or involving chemical reactions (e.g., ozone injection) (Byrley et al., 2019; Gu et al., 2020; Morawska et al., 2013). For example, a recent meta-analysis on 3D printing that included studies in a small chamber reported average means $>10^5$ cm^{-3} (Byrley et al., 2019), whereas in our review, 3D printing led to one of the lowest average means of approximately 10^4 cm^{-3}. On the contrary, for cleaning sprays, similar concentrations were measured under real-life conditions of use (1.23 to 3.30 × 10^5 cm-3) (Vu et al., 2017; Wallace and Ott, 2011) and in a high concentration of controlled ozone (3.6 and 8.5 × 10^5 cm^{-3}) (Coleman et al., 2008). Moreover, certain factors that influence exposure have been well studied, particularly for the most documented activities, such as cooking, for which certain factors were consistent with those of previous studies. The use of a kitchen hood during cooking was highlighted as a key factor to reduce UFP exposure (Zhao et al., 2019). Switching on the hood decreased the highest mean PNC reported for grilling from 4.1 to 0.2 × 10^7 cm^{-3} (Manigrasso et al., 2017). However, keeping the kitchen window open appeared to be more efficient than a hood (70 % of PNC reduction versus 35 %) (Xiang et al., 2021). The type of energy used for cooking is also determinant and was widely studied. Analysing measurements according to the energy used (see Table A5), gas led to a much higher average of mean concentrations than electricity, as previously studied (Torkmahalleh et al., 2017). The results provided by the average of peak concentrations suggest the importance of additional parameters other than the type of energy. For example, the highest peak reported (3.54 × 10^6 cm^{-3}) was measured during the heating of a Teflon® coated pan on an electric stove without food (Ciuzas et al., 2015). This result is consistent with previous observations showing the release of UFPs during the heating of PTFE (polytetrafluoroethylene) contained in Teflon® (Johnston et al., 2000). In addition, the presence of adsorbed organic matter on pans, such as detergent residue, has also been suggested in particle formation (Torkmahalleh et al., 2017).

4.4. Further research

Apart from cooking and other activities involving combustion (smoking, combustible air-fresheners, wood burning), data are still lacking for other activities (cleaning, electric heating, personal care, printing, and DIY). More measurements could address questions related to inconsistent results for a given activity. For example, hair dryers was associated with heterogeneous PNCs. The power of the hair dryer did not appear to be determinant in UFP release. Higher peaks were reported with lower powers (1000 W and 1200 W) than with higher power (2200 W) and for similar durations of use between 5 and 10 min (Ciuzas et al., 2015; Manigrasso et al., 2017). Laser printing was also associated with a wide range of peaks. This activity has been the subject of many studies, but most did not meet our criteria, as they characterized the emission in small chambers or the measurements were performed in occupational settings (Gu et al., 2020). No mean value was reported for this process, as for most cleaning activities, DIY, and the use of hair irons and non-combustible air-fresheners. Recommendations for UFP measurement were established for workplaces and outdoor air (CEN., 2016; CEN., 2018a, 2018b), but they can also be used for indoor air. Campaigns must be carried out under real-life conditions, such as individual follow up surveys. Data on time-activity patterns must be collected to better understand UFP exposure and the determinant parameters. Online devices and smartphones can help to improve the collection of time-activity patterns (Sullivan et al., 2020). We had to discard approximately 15 field studies for which the method of collecting data did not allow us to link the measurement to a specific activity. Future research on indoor non-occupational exposure should build on recommendations made in the workplace to integrate activity with personal real-time measurement (Galey et al., 2023). Portable devices are available for personal measurement, providing information on the size and surface area (lung-deposited), in addition to the number of particles (Todea et al., 2017). Sampling techniques are available to better describe the physical/chemical characteristics of UFPs and, thus, to better understand their origin and estimate their toxicity beyond their size (Kumar et al., 2021). The standardised reporting of more contextual information and measurement results in the same detection range remains challenging, but is required to improve our understanding of indoor exposure to UFPs and its spatial-temporal evolution. Where possible, air change rate, temperature, and relative humidity in the room in which the measurements are made should be assessed. Additional information, such as the presence and type of mechanical ventilation system, the presence of air filtration, window opening, and the presence of a ceiling fan, should be reported. The background concentration should be systematically reported to constitute a reference value in the absence of a regulatory value, thereby rendering measurements more meaningful. Future studies should address these various issues. Relevant data and harmonized methods can facilitate the accurate assessment of UFP exposure in epidemiological studies. Finally, there is a massive need to extend the research to developing countries, where UFPs represent a major problem because they are largely emitted by the incomplete combustion of solid and non-solid fuels used for cooking and heating.

5. Conclusion

This is the first systematic review specific to exposure to UFPs related to indoor domestic activities. Along with the activities and processes that emit UFPs, exposure to UFPs in terms of the PNC has been well documented. The different size ranges of the measuring devices represent a limitation to the rigorous comparison of measured values. Further studies are required and challenges remain to produce relevant exposure data, but the average reported concentrations can be fed into indirect exposure assessments or used in risk estimation models. Furthermore, the hierarchisation of domestic activities could guide considerations about future prevention. This review contributes to a better consideration of exposure to UFPs as an indoor air quality issue in assessments of the health impact of UFPs.

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CRediT authorship contribution statement

Sabyne Audignon-Durand: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Olivier Ramalho:** Conceptualization, Methodology, Validation, Writing – review & editing. **Corinne Mandin:** Conceptualization, Methodology, Validation, Writing – review & editing. **Audrey Roudil:** Conceptualization, Methodology, Validation, Writing – review & editing. **Olivier Le Bihan:** Conceptualization, Methodology, Validation, Writing – review & editing. **Fleur Delva:** Conceptualization, Methodology, Validation, Writing – review & editing. **Aude Lacourt:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Supervision, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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