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Research paper

Assessment of VOCs concentrations in Spanish dwellings: Acetone, toluene, xylene, α-pinene and limonene

A. Meiss [a,*], M.S. Montaluisa-Mantilla [b], D. Guerra-Díez [a], I. Poza-Casado [a], R. Muñoz [b]

[a] GI.R. Arquitectura & Energía, Universidad de Valladolid, Spain
[b] Institute of Sustainable Processes, Universidad de Valladolid, Spain

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ABSTRACT

The presence of certain Volatile Organic Compounds (VOCs) indoors represents a potential concern for occupant health, especially in dwellings with limited ventilation. In this context, the study analyzed the presence of five health-related VOCs (Acetone, Toluene, Xylene, α-Pinene, and Limonene) in Spanish dwellings. This research addresses a significant data gap, as Spain did not participate in similar European indoor air quality campaigns (INDEX or IEA-EBC Annex 68 projects). The main objective of the study was to characterize the indoor air quality in these dwellings and compare the findings with comparable data.

The concentrations of these pollutants were measured in different rooms of 29 occupied dwellings located in a continental climate in Spain during the winter period, using solid-phase microextraction coupled with gas chromatography with a flame ionization detector (SPME-GC-FID), under typical winter conditions of reduced ventilation. The results revealed the widespread presence of some compounds in most dwellings, while others were only occasionally detected, associated with specific household activities. The main sources identified were cleaning products, cosmetics, and furnishings. Acetone and Limonene showed the highest concentrations, consistent with their frequent household use, while Toluene and Xylene demonstrated lower levels consistent with the decline in their traditional sources (paints, solvents, tobacco); α-Pinene, meanwhile, was detected at very low levels, possibly due to recent changes in household product formulations. These findings emphasise the importance of ventilation, especially during winter, in reducing VOC accumulation and highlight the need to broaden the regulatory focus on indoor air quality beyond carbon dioxide.

1. Introduction

Both the World Health Organization (WHO) [1,2] and the European Union (EU) [3–6] reports highlight the risk to human health posed by indoor air pollution. This is due to the fact that European inhabitants spend almost 90 % of their time in artificial environments. On average, people spend between 14 and 18 h a day at home [7,8], even more when referring to the most vulnerable population (elderly people, children, chronically ill people), which increases the risk associated with air pollution.

The problem of adequate ventilation is becoming more prominent due to the high airtightness and minimum flow rates requirements to meet nZEB standards in new dwellings or those that have undergone extensive renovations. It is therefore vital to ensure that Indoor Air Quality (IAQ) is maintained at a satisfactory level.

In dwellings, the quality of the indoor environment is significantly influenced by the supply of fresh air, which is required to dilute and transport contaminants that have the potential to build up in each room over time. Indoor air pollutants are the result of the inflow of contaminated outdoor air and the emission of various indoor sources, including occupant activity, building finishes and materials, beauty and cleaning products, pets and vegetation, among others.

It is imperative to understand the composition of indoor air in dwellings, with particular attention to compounds that present a health risk to occupants. Traditionally, CO_2 has been considered a good indicator for the indoor concentrations of bioeffluents and other indoor pollutants [9,10]. However, current IAQ studies have expanded the range of polluting compounds beyond CO_2 to include those pollutants that can be measured by low-cost sensors [11–17], like HCHO, TVOC, PM's, CO, O_3 and NO_2.

This monitoring, although expanded, also omits a number of compounds with a significant impact on human health. Exposure to these

* Corresponding author.
E-mail address: alberto.meiss@uva.es (A. Meiss).

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specific compounds, both short-term, medium-term and long-term, has been demonstrated to produce acute and chronic effects on human health, including asthma and allergies, as well as respiratory and cardiovascular conditions. The primary challenge lies in the accurate measurement of individual VOCs, a process that requires less readily available technology based on laboratory analytical methods involving pre-concentration and chromatographic separation. The effectiveness of the process is based on the physical separation of the components of the mixture, which are captured in adsorption tubes. This physical separation is mandatory in regulations and is also recommended in scientific research [18].

However, it should be noted that this procedure cannot be applied indiscriminately due to the need for highly specialised equipment [19]. Consequently, it is important to identify specific priority compounds for further detailed analysis. The primary challenge lies in the selection of compounds that attain discernible concentrations or that have undergone sufficient toxicological investigation, from among the nearly 1000 compounds identified in indoor air.

In this context, the European INDEX project (*Critical Appraisal of the Setting and Implementation of Indoors Exposure Limits in the EU* [3,5,6]) developed a strategy to identify supplementary health-risk pollutants in residential buildings in Europe. A rigorous set of criteria was established to refine an initial list, with the objective of identifying individual compounds (excluding mixtures such as tobacco smoke or radon). The pollutants addressed originated from indoor sources, such as building materials, consumer products, or household activities, and were related to evidence of health effects supported by toxicological or epidemiological data. The aforementioned conditions led to a list of 14 contaminants, categorized as high priority, secondary priority, and those needing further investigation into their potential effects on human health.

This list has been updated by the EBC Annex 68 project (*Indoor Air Quality Design and Control in Low Energy Residential Buildings* [6]. The selection of pollutants is consistent with the INDEX project and the guidelines established by the WHO [2], and also incorporates environmental and biological pollutants that have been identified in the aftermath of the pandemic (see Table 1).

Both projects include a significant presence of European countries, predominantly from Central and Northern Europe, with only limited

Table 1
Selected environmental and biological pollutants relevant to evaluating IAQ according to INDEX and EBC Annex 68 projects.

Pollutants		INDEX project		EBC Annex 68 project	
Carbon Dioxide	CO_2			X	a
Particulate Matter	$PM_{2.5}$, PM_{10}			X	a
Relative humidity	RH			X	a
Radon	Rn			X	a
Nitrogen Dioxide	NO_2	X	1	X	b
Carbon Monoxide	CO	X	1	X	b
Formaldehyde	HCHO	X	1	X	b
Benzene	C_6H_6	X	1	X	b
Naphthalene	$C_{10}H_8$	X	1	X	b
Acetaldehyde	CH_3CHO	X	2	X	b
Toluene	$C_6H_5CH_3$	X	2	X	b
(ortho-) α-, meta-, para-Xylene	C_8H_{10}	X	2		
Styrene	C_8H_8	X	2	X	b
Ammonia	NH_3	X	3		
Limonene	$C_{10}H_{16}$	X	3		
α-Pinene	$C_{10}H_{16}$	X	3	X	b
PAHs (Benz[a]pyrene)	$C_{20}H_{12}$			X	b
Acrolein	C_3H_4O			X	b
Trichloroethylene (TCE)	C_2HCl_3			X	b
Mold				X	c
Bioaerosols				X	c

(1) *High Priority Compound;* (2) *Secondary Priority Compounds;* (3) *Compounds requiring further study;* (a) *Environmental Pollutant;* (b) *Chemical Pollutant;* (c) *Environmental Pollutant.*

representation of Mediterranean contexts (e.g., Italy and Portugal). The absence of Spain from this initiative involves not only a lack of data but also limits the transferability of existing evidence to a residential stock with distinct building and ventilation characteristics.

Spain is characterised by a high share of multi-family apartment buildings and an ageing building stock, with a large fraction of dwellings constructed before modern energy and ventilation requirements were introduced. Consequently, many existing dwellings rely primarily on natural ventilation (manual window opening) and uncontrolled air infiltration rather than controlled mechanical ventilation, and the resulting air-exchange rates are strongly driven by occupant behaviour and outdoor conditions.

These context-specific features can affect VOC source–sink dynamics and accumulation patterns, thereby supporting the need for dedicated measurements. The only existing reference in this regard is a pioneering study of multiple organic air pollutants, which was carried out in Puertollano, in the central Iberian Peninsula, in 22 dwellings exposed to an urban industrial environment [20,21]. Therefore, incorporating the INDEX and EBC Annex 68 prioritisation frameworks into a Spanish residential field study is necessary to provide country-specific, engineering-relevant evidence for IAQ management.

2. Methodology

The EsVEN project, which stands for "Smart Ventilation for Healthy Indoor Air Quality in Spanish Homes", includes a global study on IAQ. Consequently, continuous monitoring of environmental conditions (indoor temperature, humidity and concentration of compounds measurable by low-cost sensors, including CO_2) was conducted. Furthermore, user surveys were conducted to characterise the pattern of use and ventilation of the dwellings, as well as the common use of specific cleaning products, replacement of furniture or interior finishes, and the prevalence of indoor smoking.

The study was conducted during the winter months, as dwellings typically have minimal natural ventilation, with residents often keeping their windows closed to maximise indoor temperatures. Occupants completed a survey involving user patterns and case characteristics [22]. Answers suggest that windows are often opened intermittently and at specific times of the year. This behaviour was confirmed in winter through continuous monitoring of CO_2 levels in each of the dwellings of the sample. It is understood that occupants keep windows closed in winter to stem from two key concerns: thermal discomfort and energy efficiency.

The 29 cases were selected from volunteers (non-probabilistic quota sampling scheme) in Valladolid and its metropolitan area. To reduce selection bias in sample size, recruitment followed quota targets for number of bedrooms, occupancy, construction period and type of ventilation, derived from the Spanish housing census [23] (Fig. 1).

Contaminant sampling was conducted in all cases in the living room, kitchen, and master bedroom of the dwelling, considered the most representative rooms. In each case, the sample was taken within the occupied area, away from any drafts, and centred in the room at heights between 1.00 and 1.50 m breathing zone.

It is possible to measure many of the compounds in INDEX and EBC Annex 68 reliably using either low-cost sensors or colourimetric tubes. The major challenge encountered pertained to specific compounds. The utilisation of SPME-GC-FID techniques in our laboratory enabled the concentration of efforts on the detection of five pre-selected VOCs: Toluene, Xylene, α-Pinene, Limonene and Acetone [20,24–28]. The initial four compounds are delineated in Table 1; Acetone, while not constituting a risk factor for human health under typical conditions, is associated with the presence of other factors.

In accordance with the aforementioned conditions, a brief toxicological description of these compounds can be made [29]:

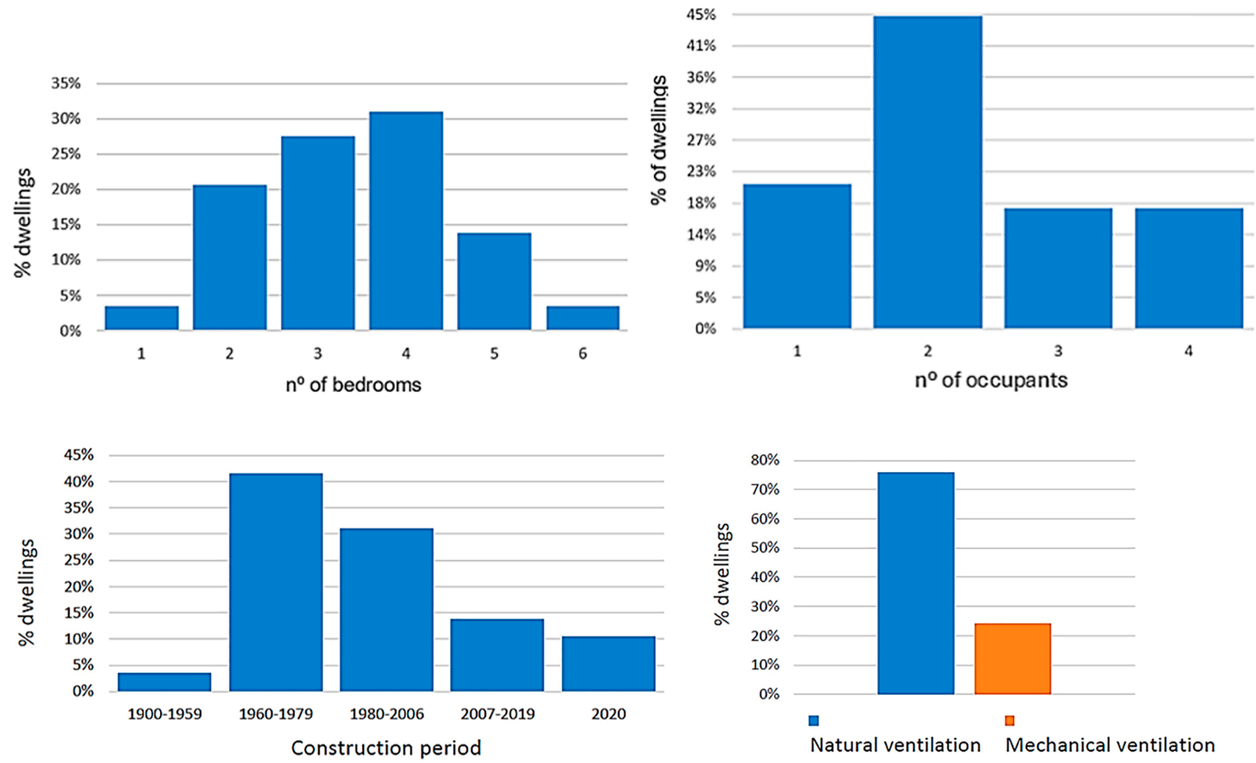

Fig. 1. Classification of the 29 dwellings tested based on the number of bedrooms, occupants per dwelling, construction period and type of ventilation.

- Toluene (CAS 108–88–3) is a highly volatile aromatic solvent used in paints, adhesives, lacquers, solvents, and fuels, which explains its common presence indoors. Low-level exposure generally has minimal effects (though it can cause odor discomfort), whereas acute high exposure may lead to fatigue, nausea, confusion, muscle weakness, loss of coordination, and, in severe cases, loss of consciousness. Chronic exposure to moderate levels has been associated with central nervous system effects, hearing loss, neurobehavioral disturbances, and liver or kidney dysfunction.
- Xylene (a mixture of (ortho-) α-, meta-, and para-Xylene isomers, was collectively considered as a combined contribution in the context of the selected HP-5 GC conditions) (CAS 1330–20–7) is a volatile aromatic hydrocarbon that is commonly present in indoor air due to its presence in paints, varnishes, solvents, fuels, and tobacco smoke. The toxicity of the compound is primarily manifested through neurotoxic and irritant effects. Exposure to moderate acute levels of the compound has been demonstrated to induce symptoms including headache, drowsiness, nausea, and irritation of the eyes and respiratory system. It is well-documented that chronic exposure to lower but sustained concentrations can have a detrimental effect on the central nervous system, with symptoms including fatigue, mild cognitive impairment, balance disorders and mood swings.
- α-Pinene (CAS 80–56–8) is a common indoor monoterpene emitted from turpentine, air fresheners, and cleaning products. At high concentrations it can cause eye, nasal, and throat irritation with mild neurological symptoms (headache, nausea, dizziness), and chronic high occupational exposure to monoterpenes has been linked to irritant-related asthma.
- Limonene (CAS 138–86–3) is a citrus-scented monoterpene widely used in air fresheners, cleaning products, and cosmetics. It has low acute toxicity, but high inhalation levels—especially under poor ventilation—can cause eye and respiratory irritation, headache, and dizziness. Importantly, it reacts with ozone to form secondary pollutants (e.g., formaldehyde and ultrafine particles) that may be more irritant and pro-inflammatory than limonene itself.
- Acetone (CAS 67–64–1) is a volatile organic solvent found in numerous domestic and industrial products and is also produced endogenously. Its toxicity is relatively low and it is efficiently metabolized and eliminated; short-term exposure may cause eye and mucous membrane irritation, headache, dizziness and drowsiness. Given its prevalence indoors and frequent contribution to overall VOC levels, it is useful for characterizing exposure patterns and source/ventilation dynamics.

A 1000 cm^3 glass bulb (Sigma-Aldrich) connected to a vacuum pump (KNF LABOPORT N 96 L) sucked air at 2 l/min^{-1} for 5 min in each room, concentrating the sample before transporting it to the laboratory. The samples were analysed in the laboratory within 24 h of collection to ensure the reliability of the results.

VOCs were quantified by Solid-Phase Micro-Extraction coupled to Gas Chromatography with Flame Ionization Detection (SPME-GC-FID). For pre-concentration, 1000 cm^3 glass bulbs were exposed for 10 min to 85 μm SPME CAR/PDMS fibers (Supelco, Bellefonte, USA). The fibers were then thermally desorbed in a GC-FID system (Agilent 8860) equipped with an HP-5 capillary column (30 m × 0.32 mm inner diameter × 0.25 μm film). The injector and detector temperatures were set at 150 and 250 °C, respectively. The oven temperature was set at 50 °C for 7.5 min, increased at 25 $°C/min^{-1}$ up to 80 °C (held for 2.5 min), and finally increased at 40 $°C/min^{-1}$ to 150 °C (held for 1 min). Helium was used as the carrier gas (3.2 mL/min^{-1}) and nitrogen was used as make-up gas (25 mL/min^{-1}). Hydrogen and air flow rates were set at 30 and 400 mL/min^{-1}, respectively. Prior to their first use, the fibers were conditioned at 300 °C for 1 h. Individual VOC standards were used for external calibration; 1 μL of each liquid-phase standard was injected into a 500 mL bulb and left at 65 °C for 3 h to ensure complete volatilization of the VOC mixture.

The calibration curves were made using four concentration levels, covering a range representative of indoor air environments (approximately 0.03–0.9 mg m^{-3}). Excellent linearity was obtained for all compounds, with coefficients of determination $R^2 > 0.99$ and detection limits (LOD > 0.03 mg m^{-3}) (Fig. 2). The repeatability of the method was evaluated based on replicate injections, which resulted in relative standard deviations (RSD) of <10 %. External calibration was applied following the recommendations of ISO 16,000–6 for the analysis of VOCs by GC. The use of flame ionization detection provides a stable and compound independent response for hydrocarbons, supporting the robustness of external calibration under the controlled analytical conditions employed.

The potential effects of the matrix were evaluated by comparing the chromatographic responses of the calibration standards with those obtained from actual indoor air samples. No significant changes in peak shape, retention time, or baseline behaviour were observed, indicating that matrix effects were negligible for the VOCs investigated.

On the other hand, to minimize potential artifacts related to sample storage or transport, glass bulbs were cleaned by passing clean air through them for 6 h, sealed immediately after sampling, and transported under controlled conditions. Samples were analyzed within a short and consistent time frame after collection. Procedural blanks and blank bulbs were analysed periodically, confirming the absence of contamination, memory effects, or analyte losses during storage and handling.

Concerning these pollutants, there are no recommended limits applicable to indoor air in dwellings; instead, they are generally focused on occupational health and safety. These recommended Exposure Limit Values (ELVs), both short and long-term, do not have a unified health reference framework and vary significantly from one organization to another (Table 2). However, they are useful for establishing a general guideline, with the caveat that sensitive individuals (elderly people, children, asthmatics) may live indoors and require lower concentrations. One possible criterion for establishing a framework may be to ensure a minimal risk by choosing the minimal value among ELVs suggested by the different organizations [30–32].

These reference thresholds were used to compare the results obtained in on-site tests in Spanish dwellings with others reported in the scientific literature.

3. Results

The outdoor air temperatures during the winter months of the study (Table 3) contributed to minimal natural ventilation rates in the dwellings, as the windows remained closed almost entirely. This has been confirmed by continuous monitoring of CO_2 levels inside each dwelling.

Fig. 3 and Table 4 summarize the concentrations measured across the 29 dwellings (considering 3 rooms in each of them) for the VOCs analyzed (Acetone, Toluene, α-Pinene, Xylene, and Limonene). VOC concentrations were summarized using medians and percentile values. Concentrations exhibited marked right-skewness, consistent with episodic indoor emission patterns. Acetone was identified as the most prevalent compound in the sample of dwellings studied (∼86 %), exhibiting a pronounced asymmetrical distribution, a consequence of the presence of elevated concentrations in specific rooms. Limonene was detected in a significant proportion of cases (∼79 %), while α-Pinene was present in a comparatively lower number of dwellings (just 4 cases, ∼14 %). The findings indicate significant variations in indoor VOC concentrations. In dwellings with no evident sources of VOC emissions, the levels of aromatic hydrocarbons (Toluene and Xylene) and α-Pinene were found to be near or below the detection limit in all rooms.

On the other hand, a set of dwellings displayed persistently high concentrations. Of particular significance is a dwelling which reported recent paint and new furnishings, and which showed some of the highest concentrations for several compounds: Acetone above ∼1210 μg/m^3 throughout all rooms, Limonene above ∼120 μg/m^3 in the living room, as well as Toluene (∼20–35 μg/m^3) and Xylene (∼36 μg/m^3).

The presence of smokers was marginal in the sample, with only one dwelling out of the total; in that dwelling, where smoking took place indoors, no significant increases in Toluene or Xylene were observed in comparison to dwellings without smokers. However, higher levels of Acetone (∼570 μg/m^3) and Limonene (∼340 μg/m^3) were detected. In any case, just one dwelling with smokers does not allow statistically significant conclusions in this regard.

Spearman's rank correlation coefficients were calculated to explore associations between the five target VOCs. Non-parametric correlation analysis was selected due to the non-normal distribution of all compounds, even after logarithmic transformation (Shapiro–Wilk $p < 0.05$ for all compounds) (Table 5). It should be noted that correlations were computed at the room level ($n = 87$), and measurements within the same dwelling are not statistically independent. Therefore, results should be interpreted as exploratory and hypothesis-generating rather than conclusive evidence of shared emission sources.

Overall, correlations were generally weak to moderate ($|\rho|$ = 0.061–0.302), indicating limited collinearity among compounds and suggesting the influence of multiple emission sources rather than a single dominant indoor source.

The positive association between α-Pinene and Limonene supports the presence of a Terpene-related emission pattern, commonly associated with cleaning products, air fresheners, fragranced consumer products, and wooden materials. The concurrent association of Acetone with both Terpenes may indicate overlapping behavioural or activity-related sources within certain indoor environments.

The inverse relationship between Toluene and α-Pinene may reflect distinct source profiles across dwellings. This divergence suggests that indoor VOC composition is not uniform but rather shaped by source-specific activity patterns.

In contrast to this, Toluene and Xylene, both aromatic hydrocarbons associated with common emission sources (paints, adhesives,

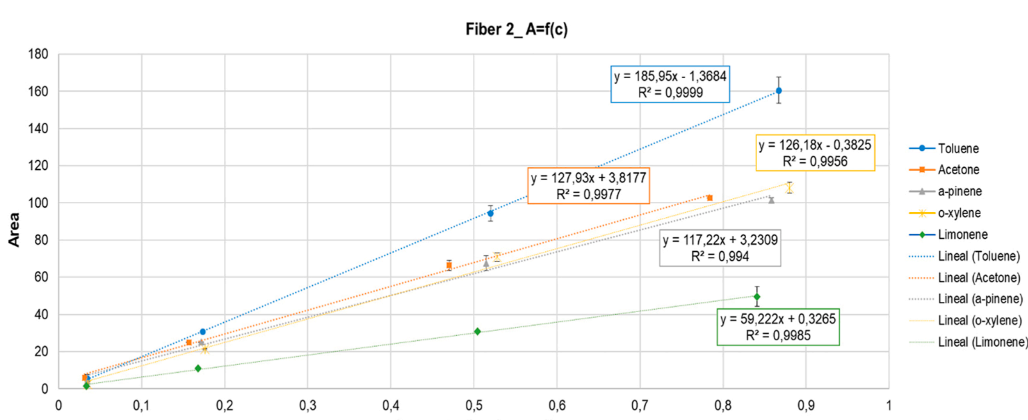

Fig. 2. Calibration curve for the model pollutants using SPME (CAR/PDMS) and GC-FID.

Table 2
Maximum recommended Short- and Long-term ELVs to the compounds studied.

Compounds	IEA EBC Annex 68	INDEX project	EU	EPA	OSHA	NIOSH	ACGIH
Acetone (C_3H_6O) CAS 67–64–1	-	84 ppm (200 mg/m^3) EL/DNEL (chronic)	500 ppm (1187 mg/m^3) TWA (8 h)	200 ppm (475 mg/m^3) AEGL-1 —— 950 ppm (2256 mg/m^3) AEGL-2 (8 h)	1000 ppm (2375 mg/m^3) PEL-TWA (8 h)	250 ppm (594 mg/m^3) REL-TWA (10 h)	500 ppm (1187 mg/m^3) TLV-STEL —— 250 ppm (594 mg/m^3) TLV-TWA
Toluene ($C_6H_5CH_3$) CAS 108–88–3	0.066 ppm (0.25 mg/m^3) LTE (1 y)	13 ppm (50 mg/m^3) LOAEL (8 h) —— 0.4 ppm (1.5 mg/m^3) EL/DNEL (chronic)	50 ppm (188 mg/m^3) TWA (8 h)	67 ppm (252 mg/m^3) AEGL-1 —— 250 ppm (942 mg/m^3) AEGL-2 (8 h)	300 ppm (1130 mg/m^3) Ceiling (15 min) —— 200 ppm (754 mg/m^3) PEL-TWA (8 h)	150 ppm (565 mg/m^3) REL-STEL (15 min) —— 100 ppm (377 mg/m^3) REL-TWA (10 h)	20 ppm (75 mg/m^3) TLV-TWA
Xylene (C_8H_{10}) CAS 1330–20–7	0.023 ppm (0.10 mg/m^3) LTE (1 y)	25 ppm (108 mg/m^3) LOAEL (8 h) —— 0.76 ppm (3.3 mg/m^3) EL/DNEL (chronic)	100 ppm (442 mg/m^3) STEL (15 min) —— 50 ppm (221 mg/m^3) TWA (8 h)	130 ppm (252 mg/m^3) AEGL-1 —— 400 ppm (1737 mg/m^3) AEGL-2 (8 h)	100 ppm (435 mg/m^3) PEL-TWA (8 h)	100 ppm (435 mg/m^3) REL-TWA (10 h)	150 ppm (655 mg/m^3) TLV-STEL —— 20 ppm (87 mg/m^3) TLV-TWA
α–Pinene ($C_{10}H_{16}$) CAS 80–56–8	0.036 ppm (0.20 mg/m^3) LTE (1 y)	90 ppm (450 mg/m^3) LOAEL (2 h) —— 0.09 ppm (0.45 mg/m^3) EL/DNEL (chronic)	-	-	(Turpentine) 100 ppm (560 mg/m^3) PEL-TWA (8 h)	(Turpentine) 100 ppm (560 mg/m^3) REL-TWA (10 h)	20 ppm (112 mg/m^3) TLV-TWA
Limonene ($C_{10}H_{16}$) CAS 138–86–3	-	80 ppm (450 mg/m^3) LOAEL (2 h) —— 0.8 ppm (0.45 mg/m^3) EL/DNEL (chronic) (INDEX) —— 0.59 ppm (3.3 mg/m^3) EL/DNEL (chronic) REACH/EU-LCI	-	-	-	-	30 ppm (170 mg/m^3) TLV-TWA (AIHA)

EU = European Union; EPA = Environmental Protection Agency (USA); OSHA = Occupational Safety and Health Administration (USA); NIOSH = National Institute for Occupational Safety and Health (USA); ACGIH = American Conference of Governmental Industrial Hygienists (USA); AIHA = American Industrial Hygiene Association STE = Short-Term Exposure; LTE (1 y) = Long-Term Exposure – 1 year exposure; EL/DNEL = Exposure Limit / Derived No-Effect Level; LOAEL = Lowest Observed Adverse Effect Level; TWA (8 h) = Time-Weighted Average - 8 h exposure; STEL (15 min) = Short-Term Exposure Limit – 15 min exposure; AEGL1 = Acute Exposure Guideline Level 1; AEGL2 = Acute Exposure Guideline Level 2; PEL-TWA (8 h) = Permissible Exposure Limit - Time-Weighted Average - 8 h exposure; Ceiling = Ceiling limit; REL-STEL (15 min) = Recommended Exposure Limit - Short-Term Exposure Limit – 15 min exposure; REL-TWA (10 h) = Recommended Exposure Limit - Time-Weighted Average - 10 h exposure; TLV-STEL = Threshold Limit Value – Short-Term Exposure Limit (15 working minutes); TLV-TWA = Threshold Limit Value - Time Weighted Average (8 working hours).

Table 3
Outdoor air temperatures on test dates [33].

Period	Absolute Minimum (°C)	Absolute Maximum (°C)	Mean Temperature (°C)	Average of Minima (°C)	Average of Maxima (°C)
21–31 January 2025	−0.9	13.1	7.6	4.3	10.9
1–14 February 2025	−1.3	14.8	5.8	1.9	9.8
15–28 February 2025	2.8	17.5	10.1	4.1	16.1
1–15 March 2025	2.5	17.1	10.7	6.1	15.3
16 Mar-1 Abr 2025	7.4	20.2	13.6	9.0	18.3

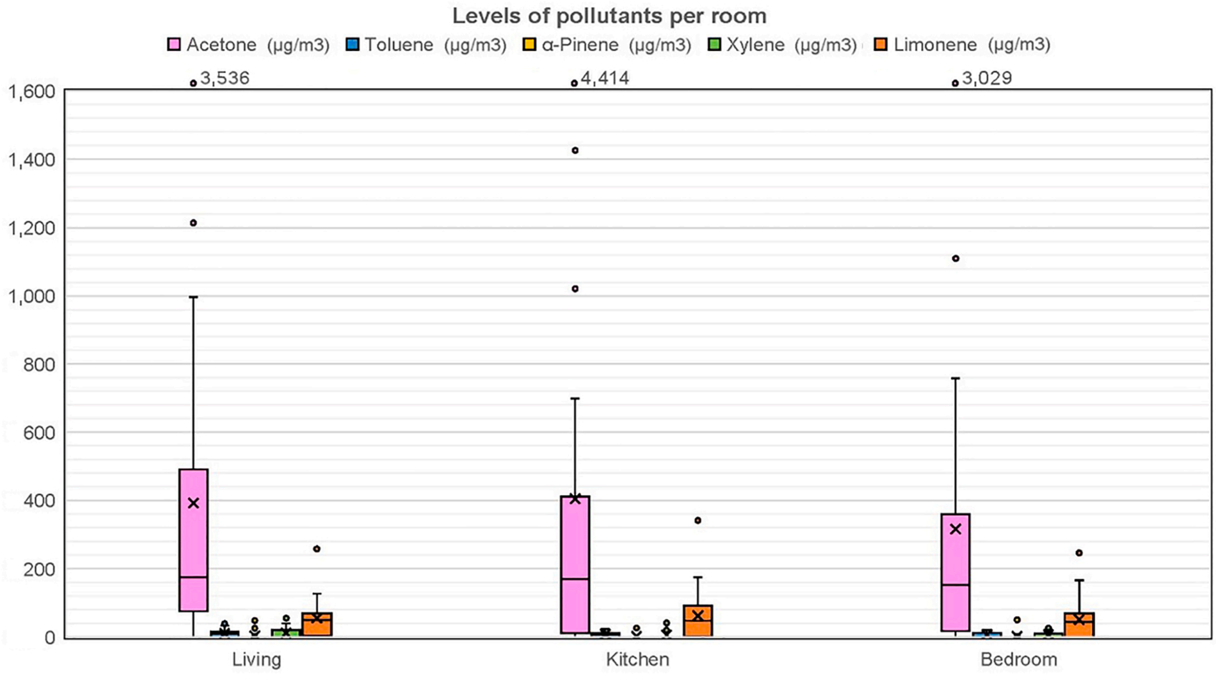

Fig. 3. Levels of pollutants per room.

Table 4
Descriptive statistics of indoor concentrations of VOCs (µg/m^3) measured.

Compound	N	Minimum (µg/m^3)	25th percentile (µg/m^3)	Median (µg/m^3)	Mean (µg/m^3)	75th percentile (µg/m^3)	Maximum (µg/m^3)	Standard Deviation (µg/m^3)
Acetone	25	0.0	45.7	177.8	371.6	403.2	4414.0	687.6
Toluene	17	0.0	0.0	7.2	8.8	12.9	48.0	11.2
α-Pinene	4	0.0	0.0	0.0	2.4	0.0	50.4	8.8
Xylene	12	0.0	0.0	0.0	8.1	14.5	61.1	14.1
Limonene	23	0.0	1.9	50.3	56.3	69.9	341.9	60.1

N indicates the number of dwellings (out of a total of 29) where the compound was detected (> 0 µg/m^3).

Table 5
Correlation - Spearman's rho (room level).

		Acetone (µg/m3)	Toluene (µg/m3)	α-Pinene (µg/m3)	Xylene (µg/m3)	Limonene (µg/m3)
	Correlation coefficient	1.000	0.107	0.272*	0.207	0.302**
Acetone (µg/m3)	Sig. (2-tailed)		0.322	0.011	0.054	0.004
	N	87	87	87	87	87
	Correlation coefficient	0.107	1.000	−0.277**	0.176	−0.207
Toluene (µg/m3)	Sig. (2-tailed)	0.322		0.009	0.103	0.055
	N	87	87	87	87	87
	Correlation coefficient	0.272*	−0.277**	1.000	0.061	0.265*
α-Pinene (µg/m3)	Sig. (2-tailed)	0.011	0.009		0.572	0.013
	N	87	87	87	87	87
	Correlation coefficient	0.207	0.176	0.061	1.000	0.172
Xylene (µg/m3)	Sig. (2-tailed)	0.054	0.103	0.572		0.112
	N	87	87	87	87	87
	Correlation coefficient	0.302**	−0.207	0.265*	0.172	1.000
Limonene (µg/m3)	Sig. (2-tailed)	0.004	0.055	0.013	0.112	
	N	87	87	87	87	87

(*) Correlation is significant at the 0.05 level (2-tailed). (**) Correlation is significant at the 0.01 level (2-tailed).

infiltration of contaminated outdoor air), were frequently detected in association in the same dwellings, although their concentrations were low and their statistical correlation was limited.

To assess whether the observed associations were driven by the dwellings mentioned with persistently elevated concentrations, a sensitivity analysis was conducted, excluding both dwellings. Overall, the sensitivity analysis supports that the reported relationships reflect consistent patterns across the dataset, although some correlations involving Acetone and Limonene were attenuated after removal of high-concentration dwellings.

To account for intra-dwelling dependence, VOC concentration measurements were aggregated considering mean concentration per dwelling and Spearman's rank correlations were recalculated at the dwelling level ($n = 29$) (Table 6).

At this aggregation scale, no statistically significant correlations were observed at the conventional α=0.05 level, which is likely

Table 6
Correlation - Spearman's rho (dwelling level).

		Acetone (μg/m3)	Toluene (μg/m3)	α-Pinene (μg/m3)	Xylene (μg/m3)	Limonene (μg/m3)
	Correlation coefficient	1.000	0.055	0.329	0.218	0.268
Acetone (μg/m3)	Sig. (2-tailed)		0.776	0.082	0.255	0.160
	N	29	29	29	29	29
	Correlation coefficient	0.055	1.000	−0.360	0.053	−0.352
Toluene (μg/m3)	Sig. (2-tailed)	0.776		0.055	0.784	0.061
	N	29	29	29	29	29
	Correlation coefficient	0.329	−0.360	1.000	0.237	0.298
α-Pinene (μg/m3)	Sig. (2-tailed)	0.082	0.055		0.215	0.116
	N	29	29	29	29	29
	Correlation coefficient	0.218	0.053	0.237	1.000	0.297
Xylene (μg/m3)	Sig. (2-tailed)	0.255	0.784	0.215		0.118
	N	29	29	29	29	29
	Correlation coefficient	0.268	−0.352	0.298	0.297	1.000
Limonene (μg/m3)	Sig. (2-tailed)	0.160	0.061	0.116	0.118	
	N	29	29	29	29	29

attributable to the reduced sample size and consequent lower statistical power. However, several moderate associations emerged and exhibited consistent directional patterns with the room-level analysis.

Furthermore, statistically significant differences between rooms (kitchen, living room, and master bedroom) were analysed by means of Kruskal-Wallis test (Table 7).

The analysis revealed no significant effect of the room ($p > 0.05$) on the level of VOCs found. These findings suggest that the distribution of the VOCs studied remains consistent across all rooms.

In conclusion, the indoor concentration data show a clear pattern of "*ubiquitous compounds*" versus "*occasionally detected compounds*". Acetone and Limonene were ubiquitous compounds, detected in most dwellings and at substantially higher concentrations compared to the other compounds. This suggests that low-level emissions of Acetone (possibly derived from human metabolism or household products) and Limonene (from cleaning products and air fresheners) are common in residential environments.

In contrast, Toluene and Xylene were more occasionally detected compounds: most dwellings had no detections, while a few showed insignificant concentrations, suggesting less widespread sources. α-Pinene was the most sporadic, with the highest levels detected in only a few dwellings. This is likely due to specific sources such as wood-derived materials and coatings (furniture, particle board, adhesives, and varnishes), as well as certain perfumed household products (air fresheners, cleaners, and deodorizers).

4. Discussion

An analysis of the results obtained in dwellings in Spain [21] and Europe [34] allows for the evaluation of the indoor air conditions in the dwellings tested. The tests carried out in Puertollano (Spain) were performed under conditions of winter environmental similarity, facilitating straightforward comparison with the Spanish case (Fig. 4).

When comparing the results of the housing tests conducted under the ANNEX 68 project, it is noteworthy that they differentiate between low-energy residential buildings (Low-E) and dwellings in conventional buildings (Non-Low-E). This distinction is particularly relevant in the context of indoor pollutants, as it signifies the presence or absence of ventilation control measures and the limitation on the airtightness of the architectural envelope. In addition, other methodological and building differences could be responsible for discrepancies in the results. While some studies focused on nationally representative housing stocks (as the UK and French National Surveys [3]), others just included specific samples such as households with children and teenagers (German Environmental Survey [3]) or newly renovated dwellings [32]. Sampling times also vary among studies, which in some cases involve time-weighted average values or short-term assessments [3].

A preliminary analysis suggests coherence among all the results, with important variations that are worth examining. Acetone, in correlation with limonene, showed the highest concentrations, mainly associated with the extensive use of cleaning products and cosmetics. Although Acetone has not been designated as a priority pollutant by the WHO, its relatively high presence has been observed to coincide with dwellings where continuous CO_2 monitoring or ventilation habits, as indicated by survey results, demonstrate a general ventilation deficit during winter months. In the case of Limonene, relatively high concentrations are consistent with its use in air fresheners, cleaning products, and detergents.

The levels of Toluene and Xylene are consistent with those reported in other studies [35], although they are in the lower range of results. These compounds, which have traditionally been associated with paints, solvents, and smoking, appear to have decreased in the years between test campaigns. A plausible explanation is the progressive reduction of Toluene and Xylene content in decorative paints/varnishes under the EU "Decopaint" Directive 2004/42/EC [36], implemented via Phase I (from 01/01/2007) and Phase II (from 01/01/2010) limit values, which promoted low-VOC product reformulation. In line with this, another factor to ponder is the reduced prevalence of smoking among adults in European countries. Thus, the low concentrations recorded in this study support the hypothesis that, at least in current Spanish dwellings, the primary sources of aromatics have been partially controlled. However, even at low concentrations, these compounds remain of epidemiological interest due to their neurological and respiratory effects in vulnerable individuals and those with chronic exposure.

Finally, α-Pinene was barely detectable in most dwellings, a finding that differs from the results of previous studies. A plausible explanation for this reduction may be due to fact that manufacturers have reduced or replaced the use of volatile monoterpenes in response to increased regulatory pressure [37,38] requiring the labelling of compounds with potential for skin/respiratory irritation or sensitization. This has led to the replacement of products based on resin derivatives with hypoallergenic fragrances or citrus fragrances (Limonene).

Table 7
Kruskal-Wallis test by room.

	Acetone (μg/m3)	Toluene (μg/m3)	α-Pinene (μg/m3)	Xylene (μg/m3)	Limonene (μg/m3)
Kruskal-Wallis H	0.742	1.630	0.684	2.677	0.535
df	2	2	2	2	2
Sig.	0.690	0.443	0.710	0.262	0.765

5. Conclusions

The concentrations of several VOCs (Acetone, Toluene, Xylene,

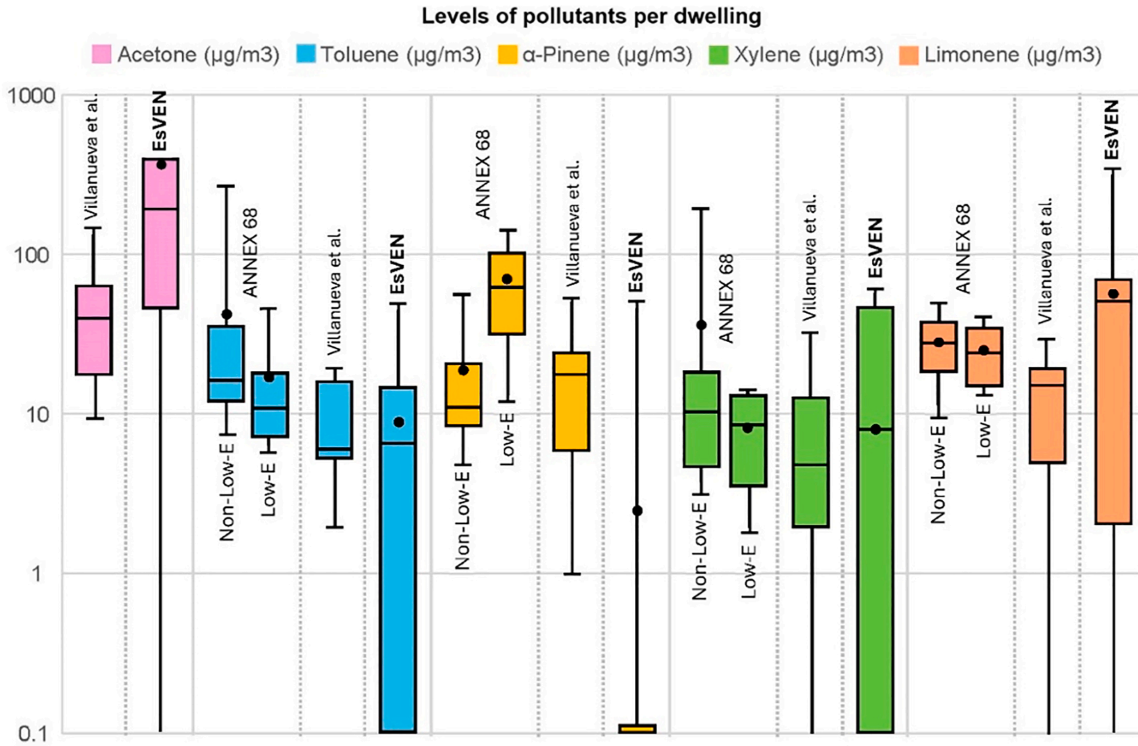

Fig. 4. Comparison of different test campaigns in dwellings.

α-Pinene and Limonene) were measured in 29 occupied dwellings located in a continental climate in Spain during the winter period using SPME-GC-FID. Although the sample size and the number of contaminants evaluated are limited, the findings of the study are as follows:

- Direct emission sources, principally cleaning products and cosmetics, may have the greatest impact on pollutant concentrations (Acetone, Toluene, Xylene, α-Pinene and Limonene).
- Inadequate ventilation during the winter months is pointed out as the cause of the accumulation of such compounds within domestic environments.
- Changes in the manner of product use in Spanish dwellings over the preceding decade could have resulted in modifications to the prevalent Terpene profile.

The risks to human health derived from the measured pollutant concentrations, although below the risk threshold due to the relatively low toxicity of some compounds, are not insignificant [19]. The presence of Terpenes, primarily Limonene, in the potential presence of Ozone, even at low levels, has been demonstrated to generate irritating oxidation products such as Formaldehyde and ultrafine particles [19]. Toluene and Xylene, although present at low concentrations, have been demonstrated to induce neurotoxic and respiratory effects in instances of chronic exposure. Finally, Acetone, although less prioritized in the toxicological literature, can act as a marker for other concurrent compounds.

The results suggest that domestic sources associated with cleanliness and personal hygiene significantly influence IAQ in Spanish dwellings and should therefore receive greater attention in current risk assessments, especially under conditions of limited ventilation, which are common in cold climates.

Further research will extend this study to include the summer period, during which interaction with the external environment is significantly increased. Occupant window-opening behaviour differs markedly from winter, with longer and more frequent opening periods—particularly at night—driven by the search for thermal comfort. Special attention will also be given to the potential influence of episodic outdoor pollution events, such as nearby wildfires and Saharan dust intrusions. Furthermore, work will be conducted on the comprehensive estimation of the IAQ through the integration of continuous pollutant monitoring and user surveys.

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CRediT authorship contribution statement

A. Meiss: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M.S. Montaluisa-Mantilla:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **D. Guerra-Díez:** Software, Investigation, Formal analysis, Data curation. **I. Poza-Casado:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **R. Muñoz:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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