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Sociodemographic and residential characteristics associated to persistent and non-persistent organic pollutants in household dust from Southern Spain. COVID-AND Study

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ABSTRACT

Background: Scientific evidence suggests that indoor dust contains chemical pollutants, such as per- and polyfluoroalkyl substances (PFAS), bisphenols, parabens, and benzophenones, which are present in building materials and everyday products and could have implications for human health.
Objective: To quantify levels of PFAS, bisphenols, parabens, and benzophenones in household dust of four cohorts from Andalusia (Spain) and determine their relationship with sociodemographic and residential characteristics.
Methods: Household dust samples (n = 102) were collected (2023- 2025) within the COVID-AND study (a multipurpose cohort whose overall aim is to investigate factors associated with Sars-CoV-2 infection in Andalusia), across four cohorts, CAPLIFE, GENEIDA, MCC-Granada, and MCC-Huelva. Target liquid chromatography–tandem mass spectrometry was used to analyze ten PFAS, two bisphenols, four parabens, and five benzophenones. Associations with log-transformed chemical levels were analyzed using robust MM-estimator regression models adjusted for sociodemographic and residential variables.
Results: Fifteen out of the 21 target chemicals were detected in all dust samples. Median concentrations ranged from 6.95 ng/g for PFHxA to 8590 ng/g for bisphenol A. High household income was positively associated with PFHxA (β:0.28, 95%CI 0.08,0.49), while University education was associated positively with benzophenone-3 (β:0.43, 95%CI 0.23,0.63). Manual work was linked to butylparaben (β:0.17, 95%CI 0.003,0.34). Densely populated areas were negatively associated with PFOA (β:-0.32, 95%CI -0.50, −0.13) and with older buildings PFOA (β:-0.007, 95%CI -0.01, −0.002)., Higher cleaning frequency was linked to benzophenone-1 (β:0.17, 95% CI 0.02,0.32).
Conclusion: Sociodemographic and residential characteristics were associated with pollutant levels in household dust. Confirming these findings in future studies will help identify population groups at high risk of exposure.

1. Introduction

Several persistent organic pollutants (e.g., per- and polyfluoroalkyl substances (PFAS)) and non-persistent organic pollutants (e.g., bisphenols, benzophenones, and parabens) are widely used in daily life. Long-term exposure to these pollutants, even at relatively low doses, has been

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associated with adverse effects in offspring and adults, increasing the risk of endocrine, metabolic, and cardiovascular diseases; reproductive disorders; and cancer (Huang et al., 2018; Demeneix and Slama, 2019; Wang et al., 2024).

These chemicals, commonly assessed via biomonitoring and diet, are also present in indoor dust (Salthammer et al., 2018), highlighting homes as potential sources of exposure, especially due to the daily use of products containing these compounds (Janousek et al., 2019; Lee and Ji, 2022; Liwara et al., 2025; Ma et al., 2025). PFAS are present in food packaging, nonstick cookware, paints, furniture, construction materials, and cosmetics products, bisphenols are used in food packaging, paints, and reusable bottles, and parabens and benzophenones are present in cosmetics and personal care products (Demeneix and Slama, 2019; EFSA, 2024; Namazkar et al., 2024; Zahm et al., 2024). Many of these pollutants exhibit semi-volatile characteristics and accumulate in household dust via air-mediated transport or direct transfer from indoor sources to settled dust (Salthammer et al., 2018; Tran et al., 2021; Lin et al., 2022).

The main exposure routes are through inhalation, dermal contact, and accidental ingestion of dust particles (Winkens et al., 2018; Sanchez-Pinero et al., 2020; Zhu et al., 2023; DeLuca et al., 2024), and given that indoor dust accumulates chemicals released in the home, it may serve as a proxy for potential human exposure (EPA, 2011). This risk is further amplified by chronic exposure associated with the extended time spent indoors (Schweizer et al., 2007). Household dust sampling has been suggested as a potentially adequate method for estimating the indoor presence and concentration of chemical substances and, thus, human exposure in this environment (Whitehead et al., 2011; Salthammer et al., 2018; Wang et al., 2025).

Given the points mentioned above, indoor dust could be interpreted as an aggregate indicator of exposure, integrating chemicals from multiple indoor sources and pathways. Contamination levels vary due to various factors. Previous biomonitoring studies, as well as studies measuring chemicals in house dust, have reported exposure patterns associated with socioeconomic characteristics. For example, lower income has been inversely associated with bisphenol A levels in biological samples (Nelson et al., 2012; Ibroci et al., 2022), whereas a higher income and educational level have been positively associated with concentrations of certain PFAS (Montazeri et al., 2019; DeLuca et al., 2024; Pineda et al., 2024; Tan et al., 2024; Wallis et al., 2024). Evidence on bisphenols and benzophenones in dust samples is scarce, and although parabens and bisphenols have been analyzed in dust (Dueñas-Mas et al., 2019; Tran et al., 2021), their association with socioeconomic characteristics remains limited. On the other hand, some studies have reported associations between certain residential characteristics, such as the degree of urbanization, flooring materials, and cleaning frequency, as well as the number of household members with some PFAS, bisphenols, and parabens detected in house dust; no consistent associations were observed for other chemical substances, and most studies had small sample sizes for indoor homes, often lower than 65 samples (Winkens et al., 2018; Sanchez-Pinero et al., 2020; Tran et al., 2021; Li et al., 2024). Studies conducted in Spanish populations have predominantly used small sample sizes and have been carried out mostly in northeastern regions. Moreover, none of these studies assessed the socioeconomic characteristics of the populations studied (Ericson Jogsten et al., 2012; de la Torre et al., 2019; Dueñas-Mas et al., 2019; Velázquez-Gómez et al., 2019; Fuentes-Ferragud et al., 2023; Haglund et al., 2024).

The present study was motivated by the adverse health effects of these chemicals and their continued widespread use in households. The aims of this study were to quantify concentrations of PFAS, bisphenols, parabens, and benzophenones in household dust samples collected from residences across a relatively wide area of Andalusia (Spain), and to explore their relationship with sociodemographic and residential characteristics.

2. Materials and methods

2.1. Study population and setting: the COVID-AND study

The COVID-AND study aimed to identify external factors associated with the prevalence of SARS-CoV-2 infection and their implications for the population in Andalusia (Southern Spain). This study was nested within four well-characterized, population-based cohorts comprising a total of 1097 healthy participants: i) Prostate cancer and lifestyle factors (CAPLIFE): a case–control study involving 430 controls from Granada (Olmedo-Requena et al., 2020); ii) Genetics, Early Life Environmental Exposures and Infant Development in Andalusia (GENEIDA): including 303 participants enrolled in a birth-cohort from Almería (Gimenez-Asensio et al., 2023); and a multi case–control Study Spain (MCC-Spain): a multicenter epidemiological case–control study, including a iii) MCC-Granada cohort from Granada with 187 controls, and a iv) MCC-Huelva cohort with 177 controls from Huelva (Castaño-Vinyals et al., 2015).

This study was approved by the Biomedical Research Ethics Committee of the Granada Province (CEIM/CEI Granada), November 30, 2021. All participants were fully informed of the study objectives and signed a written informed consent prior to their voluntary participation. Participants were assigned a numeric code, and personal identifiers were removed from the dataset to ensure data confidentiality.

2.2. Criteria selection

Study participants met the following selection criteria: 1) Adults belonging to one of the previously established cohorts included in the COVID-AND study; 2) Individuals who did not present cognitive deterioration or sensory/communication impairments that could interfere with understanding or responding to the questionnaires 3) had the capacity to voluntary and independently agree to participate and sign the informed consent; and, 4) were not institutionalized at the time the study was conducted. From the original cohorts, a subset of participants who met the eligibility criteria and agreed to participate were included in the study.

Following eligibility assessment and contact procedures, a total of 552 participants were considered eligible for inclusion. Of these, 332 (60.14%) completed a baseline questionnaire between May 2022 and December 2024: n = 208 (70.99%) in CAPLIFE; n = 41 (46.59%) in GENEIDA; n = 34 (43.03%) in MCC-Granada; and n = 49 (53.26%) in MCC-Huelva. Among those who completed the baseline questionnaire, 102 participants consented to household dust collection for chemical analysis and completed a second questionnaire on household characteristics and habits. The final sample included 51 participants from the CAPLIFE cohort (24.5%), 31 from GENEIDA birth-cohort (75.6%), 10 samples from MCC-Granada (29.4%), and 10 from MCC-Huelva (20.4%). Details of the participant selection process are shown in Fig. 1.

2.3. Data sources and variables

2.3.1. Sociodemographic and economic characteristics data

Between 2022 and 2024, participants were invited to complete a structured computerized questionnaire, administered via REDCap (Research Electronic Data Capture) (Harris et al., 2009), and 102 participants who consented to provide dust samples completed the baseline sociodemographic questionnaire either via telephone interview (38%) or online (62%). The following information was collected: sociodemographic characteristics such as age, gender, and residential area, which was classified according to the Degree of Urbanization (DEGURBA) developed by Eurostat (European Commission), which categorizes all European territory into three levels of population density (cities, towns/suburbs and rural areas) based on 1 km^2 population grid cell, and geographical contiguity criteria (Eurostat, 2021). Participants' home locations were geocoded and linked to the corresponding DEGURBA

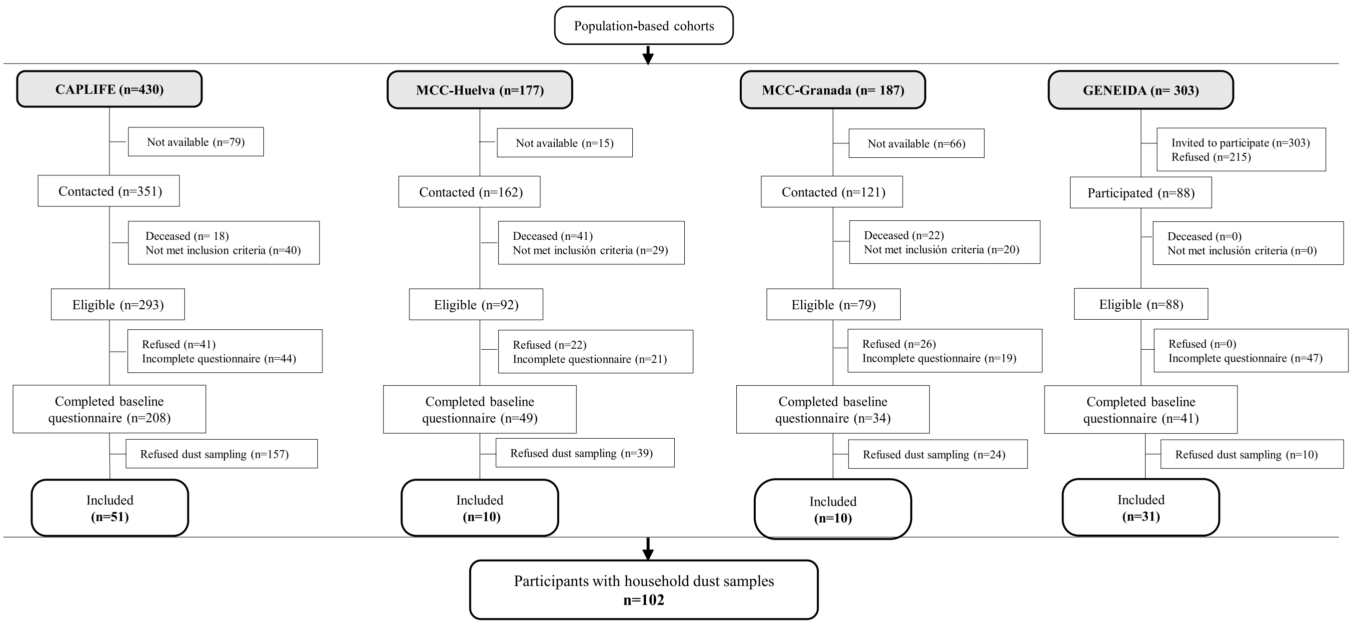

Fig. 1. Flow chart of COVID-AND study.

category, which was subsequently recategorized into two groups: densely populated areas (cities) and less densely populated areas (towns/suburbs and rural areas), according to previous methodologies (O'Callaghan-Gordo et al., 2018). Economic status data included education level (primary school or less, secondary, and university degree or postgraduate); monthly household income was defined using the square root equivalence scale, developed by the Organization for Economic Co-operation and Development (OECD). It was calculated by dividing the total household income by the square root of household size, a method that allows for comparison between households of different sizes and compositions (OECD, 2013), and was categorized into sample-specific terciles T1 (300–1000 €), T2 (1155–2125 €), and T3 (≥2454 €). Occupation type was defined according to the Goldthorpe classification, and recoded into two groups: non-manual workers (classes I–III) and manual workers (classes IV–VII) (Regidor, 2001).

2.3.2. Residential characteristics data

To identify potential sources of exposure within homes, information on household characteristics and habits was collected, following previous studies assessing indoor chemical exposure, particularly those analyzing pollutants in household dust (Karásková et al., 2016; de la Torre et al., 2019; DeLuca et al., 2024; Minucci et al., 2024; Wang et al., 2025). Several residential variables, including dwelling area (m^2), age (years), type (flat or house), and floor level (number), were verified using data from the Spanish Cadastre (Catastro Inmobiliario, 2025). All remaining variables were collected through structured interviews: household members (number of people living in the household); flooring material (natural, synthetic, or composite such as terrazzo, ceramic, porcelain tile); duration of natural ventilation in hours per week; type of house paint (plastic, acrylic, other); time since last painting (in months); cleaning frequency was derived by summing the reported weekly frequencies of sweeping, vacuuming and mopping. The resulting total number of cleaning activities per week was categorized into sample-specific terciles T1 (4–9), T2 (10–16), and T3 (≥17); presence of indoor textile, was based (sum of number of carpets, curtains, sofas, and armchairs) present in the household and categorized into sample-specific terciles T1 (1–4), T2 (5–6), and T3 (≥7), use of cookware with nonstick coating (occasionally and always/almost always); and frequency of wearing outdoor shoes at home (never, occasionally, always). Finally, the sampling date was evaluated as a potential determinant of exposure due to seasonal variability in indoor environmental conditions and household habits, which may influence pollutant concentrations. Sampling season was classified into four seasonal categories: winter, spring, summer, and autumn according to previous criteria by the Environmental Protection Agency (EPA, 2011).

2.4. Household dust sample collection

A trained researcher collected a total of 102 dust samples from inside the houses. One sample was collected per household, comprising dust from the living room and the main bedroom, the areas of the house where the participants spend most of their time, between May 2023 and March 2025, following previously described methodologies (Zhu et al., 2020; Qi et al., 2023; Li et al., 2024). All participants were instructed to avoid vacuuming or mopping their homes during the week prior to sample collection. A vacuum cleaner (Rowenta, model RO3969 EA), equipped with a 25-μm polyester filter placed in the nozzle was used to vacuum the target rooms for 5 to 8 min. Each dust sample was assigned a numeric code for identification and then, stored in aluminum foil and kept in a sealable polyethylene bag at −20 °C until analysis. Dust samples were collected according to the protocol previously described by Winkens et al. (2018).

2.5. Sample preparation and Analytical conditions

For sample preparation, 100 mg of dust was placed into a polypropylene centrifuge tube. Then, 8.0 mL of acidified acetonitrile (containing 2.5% formic acid) was added, and the mixture was vortexed for 60 s. Subsequently, 2 mL of Milli-Q water and 800 mg of NaCl were added, and the mixture was manually shaken for 60 s. The mixture was then centrifuged at 4000 rpm (2600×g) for 10 min. The supernatant was transferred to a 15 mL glass vial, concentrated to 1 mL under a nitrogen stream, and then transferred to a 1.5 mL glass vial for complete drying. The dry residue was reconstituted with 100 μL of an 80:20 (v/v) mixture of 5 mM ammonium acetate (pH 6.8) and acetonitrile, vortexed for 30 s, and prepared for Liquid Chromatography–Tandem Mass Spectrometry (LC-MS/MS) injection.

2.5.1. Chemical analysis of dust samples and chromatographic and mass spectrometric conditions

A targeted chemical analysis was carried out to identify and quantify a predefined set of chemical substances selected on their widespread use in daily use products, potential endocrine-disrupting properties, and relevance for indoor exposure (EPA, 2011; Andersson et al., 2018; Janousek et al., 2019; Liwara et al., 2025). The analysis included persistent pollutants substances: 10 PFAS; Perfluorohexanesulfonic acid (PFHxA), Perfluoroheptanoic acid (PFHpA), Perfluorooctanoic acid (PFOA), Perfluorononanoic acid (PFNA), Perfluorodecanoic acid (PFDeA), Perfluorooctanesulfonic acid (PFOS), Perfluoroundecanoic acid (PFUnDA), Perfluorododecanoic acid (PFDoA), Perfluorotridecanoic acid (PFTrA) and Perflurohexanesulfonic acid (PFHxS); and non-persistent pollutants: two bisphenols: Bisphenol A (BPA), Bisphenol S (BPS); four subclasses of parabens: Methylparaben (MeP), Ethylparaben (EtP), Propylparaben (PrP), and Butylparaben (BuP); and, five subgroups benzophenones, Benzophenone-1 (BP-1), Benzophenone-3 (BP-3), 4-Hydroxybenzophenone (4OH-BP), 2′2 Dihydroxy-4′4-dimethoxybenzophenone (BP-6), 2′2 Dihydroxy-4methoxybenzophenone-5-sulfonic acid (BP-8).

The chromatographic and mass spectrometry parameters have been previously reported (Domínguez-Liste et al., 2024). Separation was performed on a Gemini C18 column (100 mm × 2 mm internal diameter, 3 μm particle size; Phenomenex, Torrance, CA, USA) with a 20 μL injection volume and a column temperature of 25 °C. Gradient elution was applied using 5 mM ammonium acetate (pH 6.5) as the mobile phase (A) and acetonitrile as the mobile phase (B). The gradient program was as follows: 0.0–1.0 min: 30% B; 1.0–5.0 min: 30–60% B; 6.0–8.0 min: 70% B; 8.0–8.5 min: 70–90% B; 8.5–9.5 min: 90% B; then returning to 30% B over 0.1 min. The flow rate was set at 0.35 mL/min, and the total run time was 12.0 min. Analytes were detected by negative electrospray ionization in selected reaction monitoring (SRM) mode with unit mass resolution for both the Q1 and Q3 analyzers. Mass spectrometric conditions were optimized by direct infusion of 50 μg/L standard solutions. The ion source temperature was set to 450 °C and the capillary voltage to −4.5 kV. Nitrogen was used as the curtain gas at 35 psi and as the nebulizing gas at 40 psi each. All compound-specific voltages were optimized individually, with a dwell time of 20 ms per transition.

2.5.2. Method validation and analytical parameters

Method validation included evaluating accuracy, precision, trueness, limits of detection and quantification, linearity, and selectivity. Accuracy and trueness were assessed through a recovery study conducted using fortified dust samples over three consecutive days. Method precision was confirmed by relative standard deviation (RSD) values, with all values below 15%. Method trueness was supported by recovery rates ranging from 89.9% to 114.8%.

The limit of quantification (LOQ) was defined as the lowest concentration at which both accuracy and precision remained within ±20%. The limit of detection (LOD) was established as the lowest concentration producing signals at least three times higher than the background noise. LOD-LOQ (ng/g); PFAS: 0.02-0.05 and phenolic analytes: 0.1-0.4.

Good linearity was observed, with p-values >0.05 in the lack-of-fit test (Plof) and coefficients of determination (R^2) ranging from 99.1% to 99.6%. Based on these results, a linear dynamic range (LDR) was established from the limit of quantification (LOQ) up to 0.250 μg g^{-1} for PFAS and up to 20 μg g^{-1} for phenolic analytes (parabens, bisphenols, and benzophenones). Method selectivity was assessed by analyzing procedural blank chromatograms. No interferences were observed at the retention times of the target analytes.

2.6. Statistical analysis

Sociodemographic and residential characteristics were reported using means and standard deviations (SD) for continuous variables and frequencies and percentages for categorical variables. Chemical concentrations were described using the median and interquartile range [p25–p75], expressed in ng/g.

Associations between sociodemographic and residential characteristics and log-transformed chemical concentrations were assessed using robust MM-estimator regression to account for skewness, outliers, and heteroscedasticity (Maronna et al., 2019). Missing data (≤10.8%) were addressed using median imputation for continuous variables and mode imputation for categorical variables (Supplementary Material Table S1), following previously described strategies (Little and Rubin, 2019). Prior to modeling, correlations among chemical concentrations and explanatory variables were explored to characterize co-exposure patterns.

Multivariable models were fitted using a forward- and backward-stepwise approach. Models' performance was evaluated using analysis of variance (ANOVA), Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC), both adapted for robust regression based on MM-estimators (Huber and Ronchetti, 2009). Variance inflation factors (VIF) were calculated to assess multicollinearity, and the coefficient of determination (adjusted R^2) was used to estimate the proportion of variance explained. Model diagnostics were performed to assess robustness; additional details are provided in the Supplementary Material (Fig. S1). For pollutants for which the sampling season was included in the final models, sensitivity analyses were conducted by fitting the models sequentially and excluding each sampling season.

All analyses were conducted using two-sided statistical tests with a significance level set at $p < 0.05$. Statistical analyses were performed using Stata version 18 and R version 4.5.2 (StataCorp LLC, 2023; R Core Team, 2024). The following R packages were used: robustbase (Maechler et al., 2024); dplyr, tidyr, stringr, forcats (Wickham et al., 2023); ggplot2, cowplot, patchwork (Wickham, 2016); vcd, corrplot, car (Meyer et al., 2006); and sf, tmap, rnaturalearthhires (Pebesma, 2018; Tennekes, 2018; South et al., 2025).

3. Results

3.1. Sociodemographic and residential characteristics

Table 1 summarizes the sociodemographic and residential characteristics of the 102 participants. 62 (60.8%) of participants were male. Approximately 46% reported having a university education or higher, and 38% were in the lowest household income tercile (T1). A total of 53 participants (52%) lived in densely populated areas, and 58 (56.8%) resided in detached houses. The mean (±SD) home area was 182 ± 119 $m^{2,}$ and the mean of dwelling age was 1992 ± 14. Additionally, 34.3% of participants were classified in the lowest cleaning frequency tercile.

3.2. House dust samples concentration of PFAS, bisphenols, parabens, and benzophenones

House dust concentration and distribution of PFAS, bisphenols, parabens, and benzophenones are shown in Table 2 and Fig. 2. Of the ten PFAS analyzed, six were above both LOD (0.02 ng/g) and LOQ (0.05 ng/g) and detected in 100% of the samples: PFHxA; PFHpA, PFOA, PFNA, PFDeA, and PFOS. In addition, PFUnDA, PFDoA, PFTrA, and PFHxS were not detected in any of the samples. PFHxA showed the lowest concentrations, with a median [p25–p75] of 6.95 ng/g [2.51–12.56], whereas PFOA had the highest concentrations 38.66 ng/g [22.48–82.25], followed by PFDeA 28.20 ng/g [13.75–52.11].

Bisphenols A and S were detected above LOD (0.1 ng/g) and LOQ (0.4 ng/g) and were presents of the 100% of samples. Bisphenol S showed the lowest concentration, with 1400.96 ng/g [875.53–2231.90], while the concentration of bisphenol A was 8590.12 ng/g [4987.68–12515.8].

The four parabens analyzed, methylparaben, ethylparaben, propylparaben, and butylparaben, were above LOD (0.1 ng/g) and LOQ (0.4 ng/g) and detected in 100% of the dust samples. Butylparaben had

Table 1
Sociodemographic and residential characteristics of COVID-AND study (N = 102).

Sociodemographic characteristics	n (%)/Mean ± SD
Age (years)	58.5 ± 14.1
Gender	
Male	62 (60.8)
Female	40 (39.2)
Education	
≤ Primary	29 (28.43)
Secondary	26 (25.50)
≥University	47 (46.08)
Household Income € (min-max)[a]	
T1 (300-1000)	39 (38.23)
T2 (1155-2125)	36 (35.29)
T3 (≥2454)	27 (26.47)
Occupation	
No manual workers	58 (56.86)
Manual workers	38 (37.25)
Degree of urbanization	
Less densely populated area	49 (48.03)
Densely populated area	53 (51.96)
Residential characteristics	
Home area (m^2)	182.68 ± 119.65
Dwelling construction age (years)	1991.9 ± 14.05
Dwelling floor level (number)	1.30 ± 1.88
Household members	2.98 ± 1.02
Natural ventilation (hours/week)	160.76 ± 204.19
Last house painting (months)	54.29 ± 44.77
Type of Building	
House	58 (56.86)
Flat	44 (43.15)
Flooring material[b]	
Natural	25 (24.50)
Synthetic	18 (17.64)
Compound	59 (57.84)
Indoor textile presence (min-max)[c]	
T1 (1-4)	34 (33.33)
T2 (5-6)	37 (36.27)
T3 (≥7)	31 (30.29)
Cleaning activities frequency/week (min-max)[d]	
T1 (4-9)	35 (34.31)
T2 (10-16)	39 (38.23)
T3 (≥17)	28 (27.45)
Type of painting of the house	
Plastic	59 (59.60)
Acrylic	13 (13.13)
Other	27 (26.47)
Use of nonstick cookware	
Occasionally	21 (20.59)
Always/almost always	78 (76.47)
Wearing outdoor shoes at home	
Never	17 (16.67)
Occasionally	27 (26.47)
Always	55 (53.92)
Sampling season	
Winter	41 (40.19)
Spring	10 (9.80)
Summer	33 (32.35)
Autumn	18 (17.64)

n (%), number and percentage; SD, standard deviation.[a] Household Income per month (sample-[b]Flooring material includes Natural flooring (natural stone, marble, granite, wood, terracotta tile); Synthetic (synthetic parquet, laminate flooring); Compounds: (terrazzo, ceramic, porcelain tile). [c]Indoor textile presence (sample-specific terciles): sum of carpets, curtains, sofas, and armchairs. [d]Cleaning frequency (sample-specific terciles): sum of times of sweeping, vacuuming, or mopping in events per week.

the lowest concentration 765.67 ng/g [370.32–1327.32] and methylparaben the highest 3335.84 ng/g [1717.99–5771.17].

From the five benzophenones analyzed, three were above the LOD (0.1 ng/g) and LOQ (0.4 ng/g) and detected in 100% of the samples: benzophenone-1, benzophenone-3, and 4-Hydroxybenzophenone. The lowest concentration was registered for the benzophenone-1, 72.65 ng/g [48.35–111.87], and the highest for benzophenone-3, 7274.17 ng/g [4129.79–11984.05].

Table 2
Concentration levels of PFAS, bisphenols, parabens, and benzophenones (n = 102).

	Median (ng/g)	[p25–p75]
Per and Polyfluoroalkyl		
PFHxA	6.95	[2.51–12.56]
PFHpA	19.01	[9.68–27.71]
PFOA	38.66	[22.48–82.25]
PFNA	8.94	[5.13–14.57]
PFDeA	28.20	[13.75–52.11]
PFOS	15.25	[8.33–26.74]
Bisphenols		
BPA	8590.12	[4987.68–12515.8]
BPS	1400.96	[875.53–2231.90]
Parabens		
MeP	3335.84	[1717.99–5771.17]
EtP	911.50	[407.67–1509.44]
PrP	2159.90	[1246.97–3590.31]
BuP	765.67	[370.32–1327.32]
Benzophenones		
BP-1	72.65	[48.35–111.87]
BP-3	7274.17	[4129.79–11984.05]
4OH-BP	230.22	[140.71–328.79]

ng/g: nanograms per gram; p25–p75: [percentile 25–percentile75]. Limits of detection (LOD) and quantification (LOD) ranged from 0.02 to 0.05 ng/g for PFAS and 0.01 to 0.4 ng/g for phenolic compounds. All pollutants shown in the table were detected in 100% of samples. No sample showed levels of PFUnDa, PFDoA, PFTrA, PFHxS, BP-6 or BP-8 above the LOD.

Moderate correlations were observed among several PFAS, whereas correlations among bisphenols, parabens, and benzophenones were generally weak (Fig. S2).

3.3. Sociodemographic and residential characteristics associated with chemical pollutants

Multivariable robust models are shown in Fig. 3 for PFAS, Fig. 4 for bisphenols, Fig. 5 for parabens, and Fig. 6 for benzophenones.

3.3.1. Sociodemographic characteristics

In robust models including household income, PFHxA levels showed a positive gradient across income terciles, with the strongest association observed in T3 (β:0.28, 95%CI 0.08,0.49). Lower PFDeA concentrations in dust were observed in household income in the second tercile (β:−0.24, 95%CI −0.47, −0.02), whereas no significant associations were observed for PFHpA across income terciles (e.g., T3; β:0.25, 95%CI −0.01, 0.51). In addition, household income in the highest tercile (T3) was positively associated with bisphenol S (β:0.18, 95%CI 0.03,0.33) and negatively associated with butylparaben (β:−0.25, 95%CI −0.47,−0.02) and several benzophenones, including benzophenone−3 (β:−0.31, 95%CI −0.54,−0.08).

Regarding education, participants with university studies exhibited higher concentrations of butylparaben (β:0.38, 95%CI 0.17,0.60) and benzophenone−3 (β:0.43, 95%CI 0.23,0.63) in household dust, whereas participants with secondary education showed lower PFHpA and PFOA levels (β:−0.26, 95%CI −0.45, −0.07 and β:−0.25, 95%CI −0.47, −0.03, respectively). No significant associations were observed for PFNA, PFDeA or PFOS across secondary or university education (e.g., PFOS in university studies, β:0.18, 95%CI −0.01,0.38).

Participants who engaged in manual work presented slightly higher butylparaben levels (β:0.17, 95%CI 0.003,0.346) and lower PFHpA concentrations in household dust (β:−0.14, 95%CI −0.27, −0.01). Similarly, living in densely populated areas was associated with lower concentrations of several PFAS, including PFHpA, PFOA, PFNA, and PFOS. These associations consistently showed statistically significant

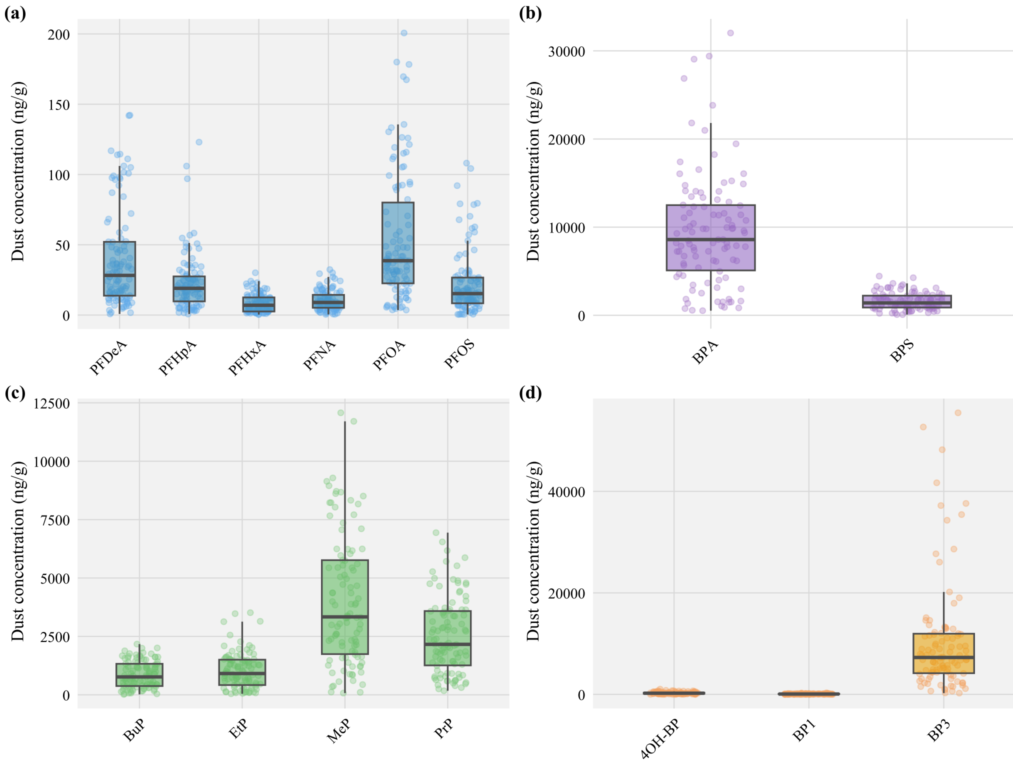

Fig. 2. Distribution of PFAS, bisphenols, parabens, and benzophenones in house dust samples (n = 102).
Panels represent a) PFAS; b) Bisphenols; c) Parabens; d) Benzophenones. Boxplots represent medians and interquartile ranges; points indicate individual distribution of sample concentrations (ng/g).

negative coefficients (e.g., PFOA, β:−0.32, 95%CI −0.50, −0.13). Bisphenol S showed higher levels in household dust in densely populated areas (β:0.11, 95%CI 0.01, 0.22).

3.3.2. Residential characteristics

In models including dwelling construction age, this variable was negatively associated with PFOA (β:−0.007, 95%CI −0.013, −0.002) and PFNA concentrations in household dust (β:−0.006, 95%CI −0.009, −0.002).

Some construction materials also showed associations. Households with composite flooring presented higher bisphenol A levels (β:0.21, 95%CI 0.04,0.37), whereas homes in the highest tercile (T3) of textile presence showed lower PFHxA concentrations (β:−0.20, 95%CI −0.39, −0.02). In contrast, no significant association was observed in PFOS levels in household dust across textile presence terciles (e.g., T3, β:0.10, 95%CI −0.09, 0.31).

Regarding residential habits, the highest cleaning frequency (T3) was positively associated with benzophenone−1 (β:0.17, 95%CI 0.02,0.32) and methylparaben (β:0.19, 95%CI 0.04,0.35). In contrast, the frequent (always or almost always) use of nonstick cookware was associated with lower PFOS levels (β:−0.22, 95%CI −0.42, −0.01). Similarly, longer natural ventilation (hours per week) was associated with lower benzophenone-3 concentrations in household dust (β:−0.03, 95%CI −0.06, −0.01). In models including sampling season, bisphenol S showed lower levels in summer and autumn than in winter (e.g., summer, β:−0.18, 95%CI −0.30, −0.06). Likewise, benzophoenone−3 showed lower concentrations in household dust in spring compared to winter (β:−0.37, 95%CI −0.61, −0.14), whereas no significant association was observed for summer (β:−0.16, 95%CI −0.37, 0.04).

No relevant associations with propylparaben were observed in the robust model. Sensitivity analyses excluding individual sampling seasons did not evidence relevant variations in the coefficients for the associations with bisphenol S and benzophenone-3 (Supplementary Material Table S2).

4. Discussion

To our knowledge, this is the largest study to date characterizing levels and factors associated with these pollutants in household dust. A key result of this study is that all analyzed households contained 15 persistent and non-persistent organic pollutants with known or suspected endocrine-disrupting properties. Several sociodemographic and residential characteristics, as well as household habits, emerged as relevant predictors of indoor concentrations, with patterns differing across chemical substances.

In this study, the highest concentrations in dust were detected for PFOA, bisphenol A, benzophenone-3, and methylparaben. Although previous studies also reported elevated concentrations of benzophenone-3 and bisphenol A in indoor dust (1230 and 1582 ng/g), respectively (Velázquez-Gómez et al., 2019; Li et al., 2022), the levels measured in this study were substantially higher (7274 ng/g of benzophenone-3 and 8590 ng/g for bisphenol A). These differences may partly reflect variations in study design, including sample sizes, geographical context, and even sampling methodology. For example, Velazquez-Gomez et al. included only 11 households in the Barcelona area in Spain, while Li et al. analyzed dust from multiple regions of China and used a different sampling method based on disposable brushes. Additional factors, such as population characteristics or residential lifestyle patterns, may also contribute to the observed differences in concentrations.

The findings of this study also highlight the presence and ubiquity of these chemical pollutants in the indoor environment, despite progressive European Union restrictions, including the limitation of benzophenone-3 (European Commission, 2022), the restriction of bisphenol A from 2018 and its complete ban in 2025 in food contact materials (European Commission, 2024) and the prohibition of PFOA since 2020 (European Commission, 2020).

Sociodemographic characteristics showed different associations with concentrations of persistent and non-persistent organic pollutants in

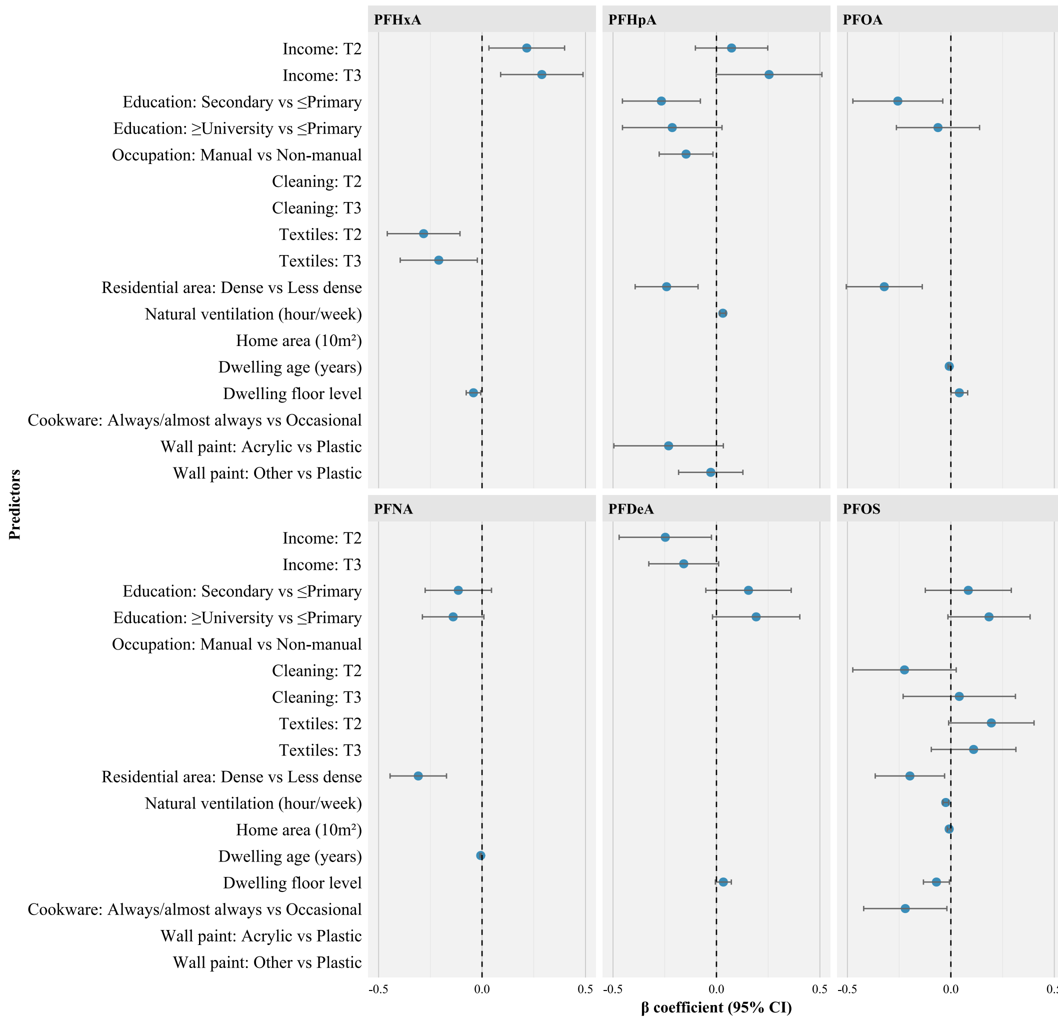

Fig. 3. Robust regression models for PFAS concentrations in household dust.
Points represent β coefficients for each covariate retained in the final pollutant-specific models. Horizontal bars indicate 95% confidence intervals. Each panel displays the predictors included in the final model for the corresponding pollutant. The home area was modeled per 10 m^2 increase. The first tercile (T1) has been used as the reference category.

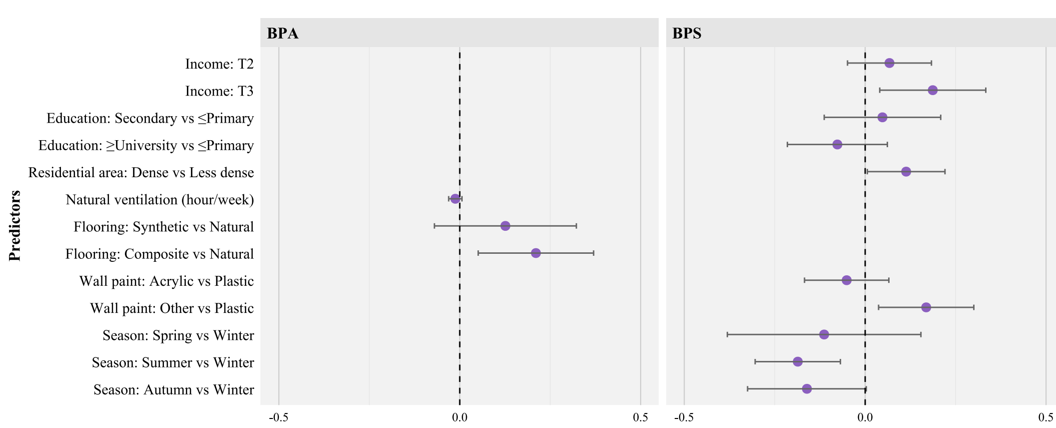

Fig. 4. Robust regression models for Bisphenols concentrations in household dust.
Points represent β coefficients for each covariate retained in the final pollutant-specific models. Horizontal bars indicate 95% confidence intervals. Each panel displays the predictors included in the final model for the corresponding pollutant. The first tercile (T1) has been used as the reference category.

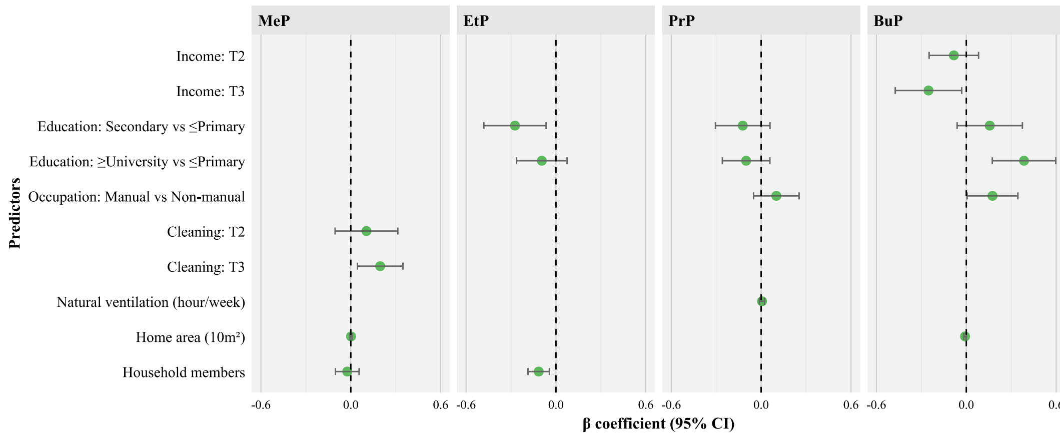

Fig. 5. Robust regression models for Parabens concentrations in household dust.
Points represent β coefficients for each covariate retained in the final pollutant-specific models. Horizontal bars indicate 95% confidence intervals. Each panel displays the predictors included in the final model for the corresponding pollutant. Home area was modeled per 10 m^2 increase. The first tercile (T1) has been used as the reference category.

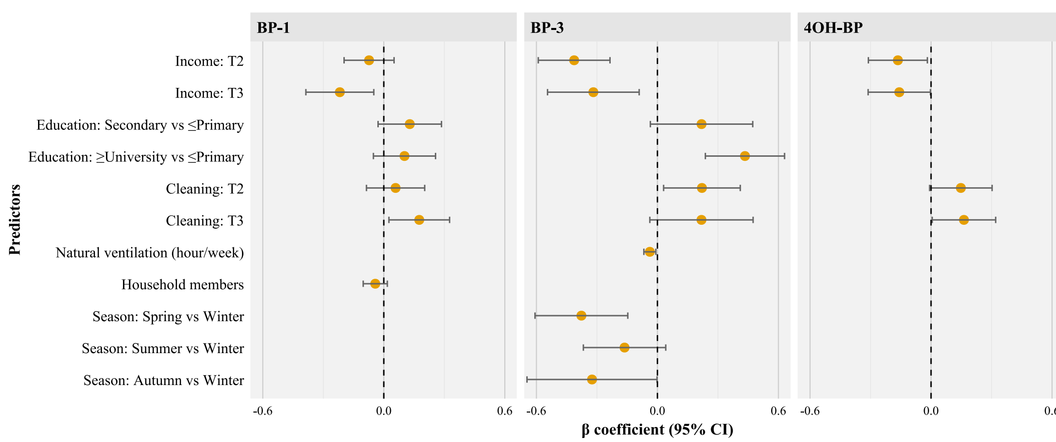

Fig. 6. Robust regression models for Benzophenone concentrations in household dust.
Points represent β coefficients for each covariate retained in the final pollutant-specific models. Horizontal bars indicate 95% confidence intervals. Each panel displays the predictors included in the final model for the corresponding pollutant. The first tercile (T1) has been used as the reference category.

household dust. Higher household income was associated with higher PFHxA concentrations, consistent with previous studies reporting higher concentrations in well water samples in wealthier areas (Kosiarski et al., 2025). In contrast, household income (T2:1155–2125 €) showed lower PFDeA concentrations in household dust. These two findings suggest that income-related differences in PFAS exposure may be pollutant-specific. The higher PFHxA levels observed in the highest income groups are consistent with the progressive replacement of short-chain alternatives, such as PFHxA, in products reformulated following regulatory restrictions on legacy PFAS (Wang et al., 2017).

Bisphenol S was also positively associated with higher household income. Although this specific association has not been consistently reported in biomonitoring studies (Lehmler et al., 2018), higher bisphenol exposure in higher-income populations and countries has been described (Moorchilot et al., 2025), likely reflecting consumption patterns and product use.

Conversely, butylparaben and benzophenones such as benzophenone-3 were present at lower concentrations among participants in the highest-income tercile. This may reflect the impact of European policies, as higher-income households are more likely to purchase newer products with lower levels of these chemicals (European Commission, 2014, 2022).

Education showed an opposite pattern, with university degrees being associated with higher concentrations of butylparaben and benzophenone-3. These pollutants are commonly used in personal care products and sunscreens and may accumulate in household dust due to their emissions into indoor air and their physicochemical properties (Wan et al., 2015; Tran et al., 2021). This finding is consistent with previous biomonitoring studies reporting higher urinary concentrations of benzophenone-3 among individuals with higher education levels, as well as a similar trend for butylparaben (Bethea et al., 2019), and with evidence of more frequent sunscreen use in this group (Alves de Menezes-Júnior, 2025). This pattern may reflect differences in personal care and sunscreen use, potentially related to greater engagement with skin care and sun protection practices across education levels.

On the other hand, manual workers showed higher butylparaben concentrations and lower PFHpA levels in household dust. Given that the exposure was evaluated in dust samples, differences observed among manual workers are unlikely to reflect occupational factors alone, but may also capture indirect exposure pathways related to differences in daily routines, including patterns of personal care product use and other household practices that may influence indoor chemical levels (Salthammer et al., 2018).

Moreover, participants living in densely populated areas (i.e., cities) exhibited lower concentrations of PFHpA, PFOA, PFNA, and PFOS. In contrast, higher bisphenol S concentrations in household dust were observed in densely populated areas, consistent with previous studies reporting higher bisphenol levels in urban compared with rural settings

(Liu et al., 2021). However, PFAS and bisphenol concentrations showed heterogeneous spatial patterns across the different regions studied. The highest PFAS levels were observed in Almería province, whereas the highest bisphenol S concentrations were in Huelva (Table S3), suggesting the influence of pollutant-specific or local factors.

Residential characteristics were associated with indoor concentrations of PFAS and phenolic compounds. Building age emerged as an important factor, with older homes exhibiting lower concentrations of PFOA and PFNA in household dust. This observation is consistent with previous studies reporting reduced PFAS levels in dust from older buildings in Central Europe and North America (Karásková et al., 2016). Nevertheless, these pollutants may still be present in certain construction materials currently in use, thereby contributing to indoor PFAS exposure (Janousek et al., 2019).

Interestingly, composite flooring materials were associated with higher bisphenol A levels in dust, supporting evidence that certain flooring types can transfer bisphenol A into the indoor environment (Ma et al., 2025). In contrast, PFHxA concentrations were lower in homes with the highest textile presence. This association is consistent with a recent European analysis of consumer textile materials (carpets, curtains, and sofas) which reported substantially higher levels of volatile PFAS, such as fluorotelomer alcohols (FTOHs) commonly used in textile treatments, compared to much lower levels of carboxylic acids, such as PFHxA (Liwara et al., 2025). Rather than indicating direct emissions of PFHxA from textiles, this pattern may suggest that these materials do not represent a major source of PFHxA in indoor environments, and other sources may play a more relevant role in household exposure.

Cleaning frequency was positively associated with methylparaben and benzophenone-1, which is consistent with their potential release from cleaning products. The findings may reflect the use as preservatives and antimicrobial agents additives in house cleaning formulations (Lee and Ji, 2022). Conversely, participants reporting more frequent use of nonstick cookware exhibited lower PFOS concentrations than occasional users. This pattern may reflect the progressive replacement of long-chain PFAS in consumer products, including cookware, with more frequent users more likely to own newer products free of long-chain PFAS (e.g., PFOS and PFOA). Following the European Union's 2020 restriction, long-chain PFAS have been progressively phased out and replaced by other PFAS compounds, such as perfluoroether carboxylic acids (PFECAs), for fluoropolymer production (Wang et al., 2017; European Commission, 2020). Continued monitoring of these replacement PFAS is essential to understanding evolving exposure patterns.

Lower concentrations of bisphenol S and benzophenone-3 were observed in dust samples collected during autumn and spring compared with those collected in winter. Along with the observation that longer periods of natural ventilation were associated with lower benzophenone-3 levels, these results underscore the importance of natural ventilation in reducing indoor exposure, which is indeed typically less frequent during the winter months.

The interpretation and comparability of pollutant concentrations across studies depend in part on the methodological approaches used to collect and analyze indoor dust. In this study, a standardized and validated vacuum-based dust sampling method was applied according to previous methodologies (Winkens et al., 2018), using the same type of vacuum cleaner and the same trained researcher to collect samples across all households, ensuring consistent dust collection. However, other studies have used different methodologies, including surface wipes, swabs, or disposable brushes (Zhu et al., 2020; Li and Chen, 2023), dust collected from specific household surfaces using targeted surface-based sampling approaches (Minucci et al., 2024), or dust samples collected by participants using their own vacuum cleaners (de la Torre et al., 2019). These methodological differences may influence the characteristics of the collected dust and the reported concentrations. These considerations highlight the need to establish clear, standardized criteria for household sampling to ensure accurate representation of exposure and improve comparability across studies.

This study has some limitations to consider: i) although standardized and validated dust collection methodology and information on potential indoor sources were used, information on the specific use of cleaning products and personal care items was not collected; ii) only one dust sample per home was collected, which may not fully capture long-term exposure and could have introduced exposure misclassification; iii) several socioeconomic questionnaire items (household income, education level, occupation) and household habits were self-reported, which may have introduced some misclassification bias. Nevertheless, key residential variables were verified using cadastral data; and iv) although this study was not designed to obtain a representative sample of the Andalusian population, the voluntary participation may have introduced selection bias, as more motivated or environmentally conscious individuals could be overrepresented.

This study also has several advantages, including the following: i) it is one of the few studies in Spain to comprehensively analyze four families of chemical substances in the indoor dust samples collected across multiple provinces. This geographic spread allows for a wider characterization of contaminant distribution and related variables; ii) this study explores an understudied aspect by examining indoor dust in relation to sociodemographic characteristics, whereas most previous dust studies have focused on relationships with residential or household practices; iii) although 102 dust samples may appear modest, this sample size is larger than that of many existing investigations in the field.

5. Conclusion

This study confirms the high prevalence of the target pollutants in household dust. Certain sociodemographic and residential characteristics were associated with chemical levels. These results contribute to characterizing exposure and identifying specific population groups with higher exposure levels, as well as to prioritizing public health campaigns. However, further studies are needed to explore in greater depth the specific factors associated with this exposure and its potential health implications.

Ethics statement

This study was approved by the Biomedical Research Ethics Committee of the Province of Granada (CEIM/CEI Granada), November 30, 2021.

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CRediT authorship contribution statement

María Ángeles Castillo-Hermoso: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Juan Pedro Arrebola:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing. **Malak Kouiti:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Rocío Capelo Álvarez:** Writing – review & editing. **Beatriz González-Alzaga:** Writing – review & editing. **Gemma Castaño-Vinyals:** Writing – review & editing. **Rocío Olmedo-Requena:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

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Glossary

BP-1 Benzophenone-1
BP-3 Benzophenone-3
BP-6 Benzophenone-6
BP-8 Benzophenone-8
BPA Bisphenol A
BPS Bisphenol S
BuP Butylparaben
DEGURBA Degree of urbanization
ECHA European Chemicals Agency
EPA United States Environmental Protection Agency
EtP Ethylparaben
LC-MS/MS Liquid Chromatographic–Tandem Mass Spectrometry
LDR Linear Dynamic Range
LOD Limit of Detection
LOQ Limit of Quantification
MeP Methylparaben
OCDE Organization for Economic Co-operation and Development
PFDeA Perfluorodecanoic acid
PFDoA Perfluorododecanoic acid
PFECA Perfluoroether carboxylic acid
PFHpA Perfluorohexanoic acid
PFHxA Perfluorohexanoic acid
PFNA Perfluorononanoic acid
PFOA Perfluorooctanoic acid
PFOS Perfluorooctanesulfonic acid
PFTrA Perfluorotridecanoic acid
PFUnDA Perfluoroundecanoic acid
PrP Propylparaben
SRM Selected Reaction Monitoring
4OH-BP 4-Hydroxybenzophenone

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2026.124825.

Data availability

Data will be made available on request.

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