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Comprehensive analysis of particulate matter, gaseous pollutants, and microbiological contamination in a clothing store from an international chain in Europe☆

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A R T I C L E I N F O

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A B S T R A C T

In this study, indoor air quality was assessed in a store belonging to one of Portugal's largest commercial retail groups. A variety of methodologies was used, including gravimetric analysis for particulate matter (PM), optical monitors for real-time PM measurements, gas sensors and analysers for CO_2 and other gaseous pollutants, diffusion tubes for VOCs, and passive deposition for microorganisms. The average PM_{10} concentration indoors was 16.5 ± 3.87 μg/m^3, well below the exposure limits set by various international organisations. A significant portion of indoor PM_{10} – 69% - was originated from outdoor sources. Outdoor PM_{10} concentrations were substantially higher, averaging 29.4 ± 14.6 μg/m^3. Metal concentrations were also higher outdoors than indoors, and the associated cancer risk and hazard quotient were not exceeded, indicating favourable air quality conditions within the store. Among VOCs, α-pinene and tetrachloroethylene were detected in notable concentrations. α-Pinene likely originated from cleaning products and fragrances, while tetrachloroethylene was attributed to emissions from a dry-cleaning establishment located in the same building, but did not exceed protection thresholds. Microbial analysis showed low concentrations of both fungi and bacteria. However, fungal species with clinical and toxigenic potential were found. The most common fungal species were *Trichoderma* sp. and *Penicillium* sp., depending on the culture media. Overall, the clothing store demonstrated good air quality. However, to further reduce the impact of outdoor pollutants on indoor air quality, enhancements to the ventilation system are recommended. These improvements can help create a healthier indoor environment by filtering and managing the intake of external contaminants more effectively.

1. Introduction

There are many different types of retail stores worldwide. Given this high level of variability, a diverse range of indoor environments, products, and services can be expected. Consequently, these environments are susceptible to various air pollutants, with particulate matter (PM) being particularly significant due to its detrimental effects on human health. Studies have linked particulate matter exposure to serious health issues, primarily cardiopulmonary disorders (Fiordelisi et al., 2017), as well as other inflammatory responses (Wu et al., 2018). Therefore, the complexity of particulate matter makes its characterisation and study essential to understanding its effects on both consumers and workers in these microenvironments.

In addition to particulate matter, CO_2 and a variety of volatile

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organic compounds (VOCs) are frequently found in the indoor air of retail environments (Robert et al., 2021). Monitoring these compounds is crucial for understanding both ventilation efficiency and the emissions of specific indoor pollutants, such as formaldehyde and tetrachloroethylene, which are known to pose health risks. Along with air pollutants, thermal comfort parameters are also essential, as they are two key variables that significantly affect human well-being (Mujan et al., 2019). Furthermore, fungi and bacteria can be found in a wide variety of environments and are also related to other variables such as ventilation and particulate matter (Kwan et al., 2020).

Among various retail environments, clothing stores hold particular significance in daily life, as clothing is essential for participation in society. It has been proven that fabrics are prone to emitting and carrying various atmospheric pollutants. A study by Ferro et al. (2004) examined the contributions of various household activities to particulate matter levels, revealing that tasks involving the manipulation of fabrics, such as clothes and sheets, emit high concentrations of particulate matter. During these activities, concentrations of particulate matter with a diameter lower than 10 μm (PM_{10}) often exceed 200 μg/m^3. This occurs not only because of the composition of the clothes, but also because fabrics are reservoirs of particulate matter that can be transported from one place to another or even accumulate on their surface and be released after disturbance (Licina and Nazaroff, 2018).

Jhang et al. (2023) conducted a controlled study using mannequins dressed in various outfits and observed a higher deposition coefficient for larger particles. Their findings indicated that wool and fleece tend to retain higher concentrations of particles compared to polyester and cotton. Also, Kim et al. (2024), studying several stores in shopping centres, including clothing and accessories stores, found higher concentrations of particulate matter lower than 2.5 μm ($PM_{2.5}$) in restaurants than in clothing shops, suggesting that the particles in these stores may be larger than $PM_{2.5}$. Robert et al. (2021), studying VOCs in several retail stores, found that clothing stores, particularly in the storage area, have elevated concentrations of formaldehyde and benzene.

The current study represents a collaborative effort among multiple research groups to assess indoor air quality in retail environments that are less frequently explored in existing literature. This approach is particularly relevant given that the predominant composition of clothing - cotton, polyester, wool, and nylon - is commonly found in most clothing shops. By focusing on these environments, the study aims to deepen the understanding of particulate matter and gaseous pollutants in these stores. In addition to focusing on a commercial environment that has been little studied, the originality of this study lies in the fact that the air quality assessment was conducted simultaneously indoors and outdoors, considering not only regulated pollutants but also components that are not part of the regulatory framework and are therefore typically not monitored (e.g., PM-bound chemical constituents, speciation of carbonyls, and other VOCs). This approach allows for inferences about sources and potential health effects, providing support for decision-making regarding any necessary interventions.

2. Methodology

2.1. Sampling site and local characteristics

This study was carried out in a clothing store belonging to one of Portugal's largest supermarket chains, which is also represented in other countries. Since it is part of a franchise, all the other shops in the same company have similar environments. The store opens from 09:00 a.m. to 08:00 p.m., Mondays to Sundays, and does not close for lunch. The store is located in the north-west of Portugal, in the Bragança district, a region with well-defined seasons, characterised by significant temperature amplitudes between the colder and warmer months, with precipitation predominantly occurring during the autumn and winter seasons (Gonçalves et al., 2018).

The store is situated within a larger building that also houses a supermarket, a home and kitchen appliances store, a laundry service, and an electronics store. This facility is equipped with an air conditioning system designed to regulate indoor temperature, and the entrance has two sets of doors that help minimise outdoor air intrusion and maintain climate control. The building is located in an industrial area predominantly comprised of commercial and service-oriented establishments, as well as small industries that do not emit significant levels of air pollutants. The local air pollution is primarily associated with commercial activities, traffic and biomass burning, as documented by Cipoli et al. (2022). In this region, biomass burning is commonly used for domestic heating, particularly during the autumn and winter months (Cipoli et al., 2023, 2022). The industrial area is far from the city centre, with a substantial volume of traffic observed primarily during rush hours: 07:00 a.m. to 09:00 a.m., 12:00 a.m. to 2:00 p.m. and 5:00 p.m. to 7:00 p.m. The buildings surrounding the establishment targeted in this study are not classified as sources of atmospheric pollutants and the region is sporadically influenced by desert dust intrusion events, which significantly increase the concentrations of particulate matter and some of its constituents, especially Al, Ca, and Fe (Cipoli et al., 2023). These events are well-documented across the Iberian Peninsula (Fernández et al., 2019; Pereira et al., 2008), and represent an important phenomenon that impact the overall air quality. The most common periods for African dust intrusions typically occur during the spring and summer, with a higher frequency between March and September.

2.2. Sampling and instrumentation

This study utilised three methodologies to assess the indoor air quality of the clothing store. To monitor particulate matter, gaseous pollutants, and thermal comfort parameters, a cabinet equipped with various instruments was used. The setup included: i) a 38.3 L/min sampler (ECHO PM, Tecora) for PM_{10} sampling on 47 mm quartz filters; ii) one particulate matter monitor (OPS 3330, TSI); iii) and an indoor air quality probe (WolfSense IQ-610, GrayWolf) for measuring CO_2 and total volatile organic compounds (TVOCs). This cabinet was positioned in the centre of the store in accordance with the 2004 ISO 16000-1 standard (Indoor Air – Part 1: General Aspects of Sampling Strategy) and remained in place from September 29 to October 12, 2022. Simultaneously, a similar setup was deployed outdoors, using a low-volume 38.3 L/min sampler (ECHO PM, Tecora) for PM_{10} sampling and a particle monitor (DustTrak DRX 8533, TSI). A total of 24 filters were collected during this period, 12 from indoor and 12 from outdoor, with 9 samples taken during opening hours and 3 during closing hours. Additional data were gathered from gas analysers near the study site, including a NO_X analyser (HORIBA, APNA-370) and an O_3 analyser (HORIBA, APOA-370). Meteorological data, such as temperature, humidity, rainfall, solar radiation, wind speed, and direction, were also incorporated.

Data from particle optical monitors were validated by calibrating them against gravimetric measurements. The OPS 3330 and DustTrak DRX 8533 particle monitors, manufactured by TSI, were factory-calibrated before the monitoring campaign. The WolfSense monitor underwent a multipoint calibration process to enhance its precision. Calibration of the CO_2 probe was performed using standard gas bottles with concentrations of 347 ppm, 803 ppm, and 2484 ppm. The CO probe was calibrated by zeroing with pure nitrogen (N_2) and a 7.9 ppm CO standard. Similarly, the TVOC probe was calibrated by establishing a zero point with N_2 and using isobutylene at concentrations of 96.1 ppm and 251 ppm.

The second methodology involved passive sampling of gaseous pollutants using diffusive cartridges (Radiello codes RAD145 and RAD165) to capture VOCs and carbonyls. Two samplers of each type were installed indoors from October 4 to October 16, 2022, and one of each was installed outdoors from October 4 to October 21, 2022. Blank diffusive tubes were used alongside the samples to account for potential contamination or background interference during the sampling process.

Lastly, the third component focused on the passive collection of microorganisms at six locations within the store, using electrostatic dust collectors (EDCs) with a 140 mm diameter. Additionally, 110 mm quartz fibre filters were placed alongside the EDCs to assess particulate matter deposition from October 4 to December 15, 2022.

2.3. Analytical procedures

The quartz fibre filters were weighed using a high-precision microbalance with and accuracy of 1 μg (RADWAG, MYA 5/2Y/F), and the mass was determined by averaging six measurements after stabilisation in controlled conditions (20 °C, 50% relative humidity). To quantify the carbonaceous content of PM_{10} samples, a thermo-optical method was applied. This technique differentiates between organic carbon (OC) and elemental carbon (EC) by sequentially heating small filter sections in an inert nitrogen atmosphere (100%) to volatilise OC, followed by oxidation in an atmosphere containing 4% oxygen and 96% nitrogen to measure EC. Both OC and EC were quantified as CO_2 using a Fourier-Transform Infrared (FTIR) gas analyser. However, due to the limited sample mass on the filters, it was difficult to distinguish between OC and EC. As a result, only total carbon (TC) was determined. By analysing replicate samples, the accuracy of the thermo-optical instrument was estimated to be ±5%. The elemental composition of the quartz fibre filters, including the elements S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Br, Pb, and Sr, was determined through X-ray fluorescence (XRF) analysis using an ARL Quant'X EDXRF spectrometer (Thermo Scientific Inc.). Further details on this methodology are provided by Chiari et al. (2018). The ED-XRF instrument was regularly calibrated using pure thin film standards (Micromatter– XRF Calibration standards, 50 μg/cm^2, N – Nuclepore® polycarbonate aerosol membranes, USA) and the NIST SRM2783 standard (Air Particulate on Filter Media). Detection limits for the analysed elements were in the range from 3 to 12 ng/cm^2. Several blank filters were treated in the same way as the samples, and the average concentrations of carbon and elements determined in them were subtracted from those obtained in the PM_{10} filters.

The analysis of the diffusive tubes was conducted by Fondazione Salvatore Maugeri (Padova, Italy). Carbonyls were extracted using acetonitrile as a desorption solvent and analysed by high-performance liquid chromatography (HPLC). VOCs were analysed via thermal desorption coupled with gas chromatography-mass spectrometry (GC/MS). Generally, Radiello diffusive tubes are known for providing reliable passive sampling data with a typical accuracy range of about ±10–15% for many VOCs and carbonyls.

For the EDC samples, a NaCl saline solution was used for extraction, and the samples were then inoculated onto four different culture media. Fungi were cultured on malt extract agar (MEA) and dichloran-glycerol agar (DG18), while bacteria were grown on tryptic soy agar (TSA) and violet-red bile agar (VRBA). After incubation, the densities of fungi and bacteria were assessed. Fungal species or sections were identified microscopically based on macroscopic and microscopic characteristics, following Hoog et al. (2000). Also, the 110 mm quartz fibre filters used together with the EDCs were weighted using the same methodology as the regular 47 mm filters. Blanks were also cultivated in the same media to assess any contamination.

2.4. Data analysis

Data from continuous monitoring equipment were used to develop temporal profiles. Since the clothing store operates daily from 9:00 a.m. to 8:00 p.m., these hours were used to construct daily patterns. Spearman's correlation coefficients were calculated to examine the relationships between variables, with significance levels set at 0.05, 0.01, and 0.001 in a two-sided test. In addition to the indoor/outdoor (I/O) ratio, the enrichment factor (EF) was calculated for each element relative to its concentration in the Earth's crust, based on equations from Zoller et al. (1974), to identify their potential sources.

$$EF = \frac{(X/Fe)_{air}}{(X/Fe)_{crust}} \quad (1)$$

where $(X/Fe)_{air}$ represents the ratio of element X to the concentration of Fe within the same sample, and $(X/Fe)_{crust}$ refers to the ratio of element X to Fe in the Earth's crust. In this study, Fe was used as a reference, and Ca served as a comparative element. To classify EFs, the categories proposed by Sutherland (2000) were applied: EF $<$ 2 indicates depletion to minimal enrichment (no or minimal pollution); EF between 2 and 5 signifies moderate enrichment (moderate pollution), EF in the range of 5–20 corresponds to significant enrichment (significant pollution), EF between 20 and 40 represents very high enrichment (very strong pollution), and EF $>$ 40 indicates extreme enrichment (extreme pollution). Furthermore, Chiarenzelli et al. (2001) suggest that EF $>$ 10 typically points to substantial contributions from anthropogenic sources.

The CO_2 decay method was applied to calculate the building's ventilation rate (Batterman, 2017):

$$ACH = \frac{\ln((C_1 - C_R)/(C_0 - C_R))}{t} \quad (2)$$

where ACH is the air change rate per hour (h^{-1}), C_0 and C_1 are the CO_2 concentrations measured during the decay period (usually at night, when the store is unoccupied), C_R is the reference CO_2 concentration, representing the value at low occupancy, and t is the measurement time (hours) between time 0 and 1.

To express ventilation in L/s·m^2 for comparability with other ventilation metrics, the following equation (modified from WHO, 2009) was used:

$$Ventilation\ rate \left(\frac{L}{s\ .\ m^2}\right) = \frac{\text{AER}\ .\ height\ (m)}{3.6} \quad (3)$$

Additionally, the infiltration factor was calculated using the following equation (Rivas et al., 2015):

$$C_{in} = F_{inf}\ .\ C_{out} + C_{ig} \quad (4)$$

where C_{in} is the indoor particulate matter concentration; C_{out} is the outdoor particulate matter concentration; F_{inf} is the infiltration factor; C_{ig} is the concentration of particles generated indoors, which is obtained as the slope of the correlation line between indoor and outdoor concentrations. In this study, the average C_{ig} was 4.77. The contribution of outdoor particles to indoor PM concentrations was estimated as follows (Lv et al., 2017):

$$\rho = \frac{(F_{inf}\ .\ C_{out})}{C_{in}}\ .\ 100 \quad (5)$$

The noncarcinogenic and carcinogenic risks associated with inhalation exposure to trace elements in indoor PM_{10} for store employees were assessed using the methodology from the United States Environmental Protection Agency (USEPA, 2009). For noncarcinogenic risks:

$$\text{HQ} = \frac{EF\ .\ ED\ .\ ET\ .\ C}{R_fC\ .\ AT} \quad (6)$$

For carcinogenic risks:

$$\text{CR} = \frac{EF\ .\ ED\ .\ ET\ .\ C\ .\ IUR}{AT} \quad (7)$$

where HQ is the hazard quotient; CR is the cancer risk; EF is the occupational exposure frequency (set to 231 days/year: 252 workdays minus 21 vacation days); ED is the exposure duration (40 years, corresponding to period of working life until retirement); ET is the exposure time (8 h/day); C is the concentration of the metal in air (mg/m^3); AT is the averaging time in hours (for non-carcinogenic effects: 365 days/year × 24 h/day × ED; for carcinogenic effects: 70 years × 365 days/year × 24 h/day); R_fC is the USEPA reference concentration (mg/m^3); IUR is the inhalation unit risk for carcinogens. Information on the reference dose for oral exposure (R_fD) and the reference concentration for inhalation exposure (R_fC) were obtained from the IRIS platform. In some cases, when R_fC was not available, it was estimated from R_fD:

$$R_fC = \frac{R_fD\ .\ BW}{IR} \tag{8}$$

where BW is body weight and IR is the inhalation rate. An average body weight of 70.1 kg for the Portuguese population was used (Rosário et al., 2018). The inhalation rate was assumed to be 0.91 m^3/h. This value was calculated as an average of sedentary and light activities based on field protocols (Table 6-43, USEPA, 2011).

3. Results and discussion

3.1. Meteorological variables and indoor thermal parameters

Given that the store operates daily at the same hours, daily profiles were created to visualise the variation of both indoor and outdoor pollutants, along with relevant weather parameters. Fig. S1 of the supplementary material presents the temporal patterns of nitrogen oxides, ozone, temperature, relative humidity, rainfall, solar radiation, and wind speed throughout the day.

During the study, conducted at the beginning of autumn, outdoor temperatures ranged from 10 to 25 °C, with a minimum of 5.1 °C and a maximum of 28.1 °C. Relative humidity showed significant fluctuations throughout the day, with differences as large as 50%. Wind speed exhibited a gradual increase between 8 a.m. and 4 p.m., reaching its highest values during daytime. Sparse rainfall was recorded during this period, with no events exceeding 0.8 mm. Indoors, the average temperature was 26.6 °C, ranging from 21 °C to 29 °C, while the average relative humidity was 29.3%, with minimum and maximum values of 18.7% and 40.1%, respectively.

As observed in Fig. S2 of the supplementary material, temperature and relative humidity had just a small variability due to the central HVAC system. In relation to CO_2, the concentrations remained between 600 and 800 ppm. When compared to another clothing store with mechanical ventilation in France, the values in this study were lower, but not far from the mean value (811 ppm) of that study (Robert et al., 2021).

The air change rate (ACH) was estimated, showing an average of 0.45 h^{-1} when the store was closed and 0.96 h^{-1} when it was open. It was possible to assess the ACH during opening hours due to a linear decrease in CO_2 concentrations between 1:00 p.m. and 3:00 p.m., observed in several days. The higher ACH during open hours is attributed to the opening of doors and the operation of the air conditioning system. Based on the store's ceiling height of 6 m, a ventilation rate of 0.75 L/s·m^2 was calculated for closed hours, while 1.6 L/s·m^2 was estimated for open hours. Both values meet the requirements outlined in the ASHRAE Standard 62.1 for ventilation and acceptable indoor air quality (ANSI/ASHRAE, 2022), which recommends a minimum ventilation rate of 0.6 L/s·m^2 for retail spaces.

3.2. PM_{10} concentrations and carbonaceous content of PM_{10}

The average PM_{10} concentration in the clothing store was 16.5 ± 3.87 μg/m^3 during opening hours and 17.6 ± 3.04 μg/m^3 during closing hours. Much higher concentrations were observed outdoors, averaging 39.5 ± 24.2 μg/m^3 during the day and 36.7 ± 13.9 μg/m^3 at night. The outdoor levels were sometimes very high due to various Saharan dust intrusions. A study measuring $PM_{2.5}$ (Kim et al., 2024) also reported low concentrations of particulate matter in clothing and fashion shops, with values of 3.2 ± 2.4 μg/m^3 and 2.9 ± 2.1 μg/m^3, respectively.

In general, the daily indoor (16.8 ± 1.95 μg/m^3) and outdoor concentrations (29.4 ± 14.6 μg/m^3) were below the WHO guideline of 45 μg/m^3. Chan et al. (2016) observed a high variability in concentrations of PM_{10} in different retail environments, varying from 10 to 47 μg/m^3 in grocery stores, from 12 to 27 μg/m^3 in furniture/hardware stores, and from 7 to 30 μg/m^3 in apparel stores.

It was found that outdoor sources contributed 69% of indoor PM concentrations during the day. This indicates that more than half of the particulate matter inside the store originates from outdoor air. Both indoor and outdoor samples showed a low carbon content, with concentrations of 1.23 ± 0.51 μg/m^3 and 0.68 ± 0.53 μg/m^3, respectively. On average, TC accounted for 7.86% of the total PM_{10} mass indoors (maximum of 14.7% and minimum of 2.1%), while outdoors, the contribution was 1.91% (maximum of 4.9% and minimum of 0.2%). This low carbon concentration reinforces the previous assertion that the intrusion of mineral dust significantly outweighs the contribution of carbonaceous matter to PM_{10}. It also shows that, indoors, despite the large contribution of outdoor particles to indoor concentrations, there is an enrichment in the carbonaceous content, mostly likely due to the different fibres from the clothes. Compared with the study by Sillanpää et al. (2006), who determined the chemical composition of PM_{10} in six European cities, the values of the present study are below the TC percentage found in Duisburg (14.9%), Prague (12.8%), Amsterdam (8.6%), Helsinki (11.7%), Barcelona (10.5%) and Athens (8.3%).

The daily profile of PM_{10} concentrations is shown in Fig. 1. As described in the methodology, the clothing store is within a shared building with multiple stores, some of which began operations at 06:00 a.m., resulting in the rise of particle levels at 06:00 a.m. due to employees' activities in the building, with levels decreasing by 08:00 a.m., time when the HVAC is activated. The clothing store's shift begins at 09:00 a.m., leading to a gradual increase in PM_{10} levels throughout the day, with an average value of 16.6 μg/m^3. The values start to decrease at 6:00 p.m. reaching their minimum at 10:00 p.m. (8.74 μg/m^3). After 10:00 p.m., an increase in PM_{10} level is observed until midnight, when the concentration stabilises. The clothing store closes at 08:00 p.m., while the building remains open until 10:00 p.m. This period sees increased activity, leading to higher PM_{10} concentrations. Also, the HVAC system is turned off, and due to the tightness of the space, particles remain suspended in the air for an extended period.

3.3. Correlations and cluster analysis

The relationships between the analysed variables are illustrated in Fig. 2. Correlation coefficients were divided into five classes: 0.00–0.10 negligible correlation, 0.10–0.39 weak correlation, 0.40–0.69 moderate correlation, 0.70–0.89 strong correlation, 0.90–1.00 very strong correlation (Schober et al., 2018).

Indoor PM_{10} showed a moderate negative correlation with both indoor relative humidity (RH) (−0.58) and outdoor RH (−0.54). Higher RH values are generally associated with rainfall events, which can scavenge and reduce PM concentrations. On the other hand, higher atmospheric humidity can enhance aqueous processing, promoting the formation of larger particles through hygroscopic growth, which settles down quicker. Solar radiation and carbon monoxide (CO) exhibited weak correlations with indoor PM_{10}, with CO exhibiting an almost negligible correlation during the sampling period. However, the indirect effect of solar radiation on particulate matter concentrations is evident through its correlation with outdoor temperature. Solar radiation and outdoor temperature exhibited a moderate correlation (0.64), while outdoor temperature was moderately correlated with indoor PM_{10} levels (0.43). This may be due to the fact that solar radiation promotes photochemical reactions, which contribute to the formation of secondary aerosols. Overall, these findings highlight the complex interactions between meteorological conditions and pollutant levels, where indirect factors, such as temperature influenced by solar radiation, can affect indoor air quality concentrations.

Furthermore, indoor PM_{10} exhibited a moderate correlation with

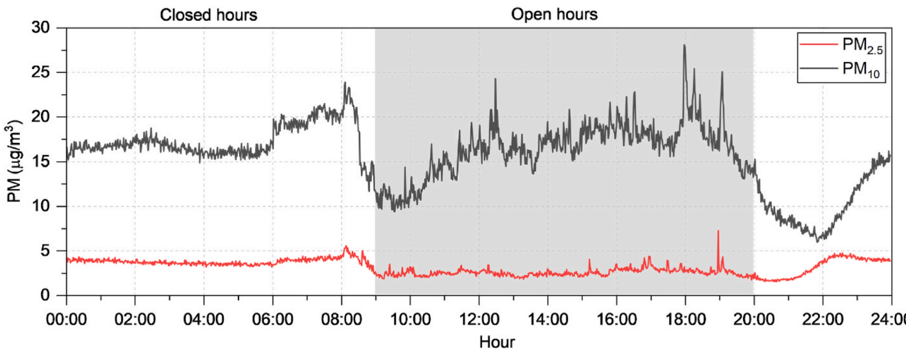

Fig. 1. Daily profile of indoor PM_{10} and $PM_{2.5}$ concentrations.

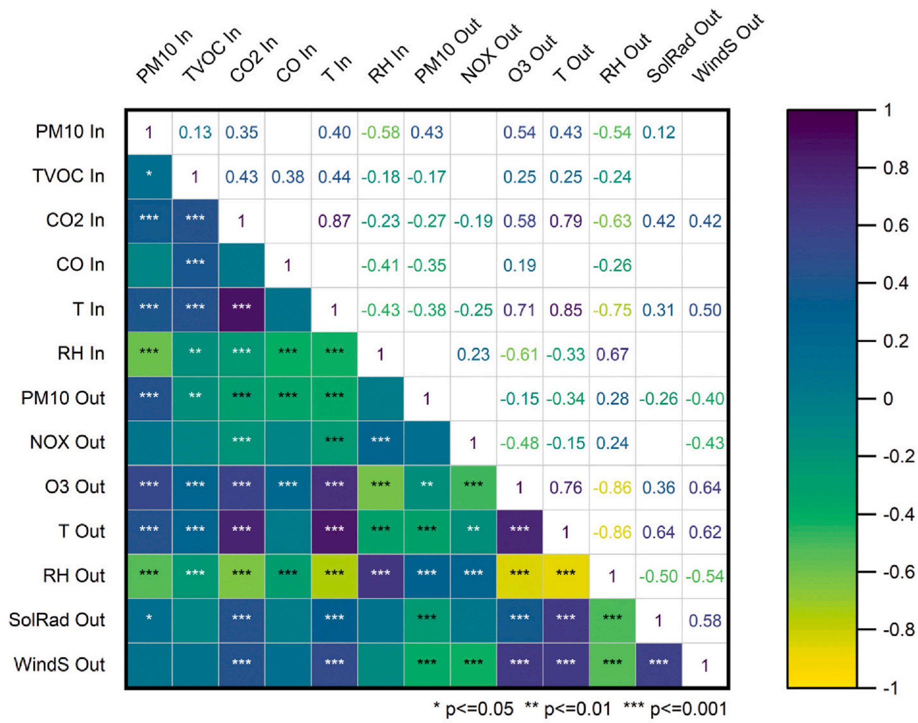

Fig. 2. Spearman correlation graph. The upper triangle shows the correlation coefficients and the lower the statistical significance of the correlations. PM_{10} In – PM_{10} indoors, TVOC In – Total volatile organic compounds indoors, CO_2 In- carbon dioxide indoors, CO In – carbon monoxide indoors, T In – Temperature indoors, RH In – Relative humidity indoors, PM_{10} Out - PM_{10} Oudoors, NO_X Out – nitrogen oxides outdoors, O_3 Out – ozone outdoors, T Out – temperature outdoors, RH Out – relative humidity outdoors, SolRad Out – solar radiation outdoors, WindS Out – wind speed outdoors.

outdoor ozone (0.54). Ozone can react with indoor surfaces or airborne VOCs to produce secondary organic aerosols (SOAs), increasing PM concentrations indoors. Higher outdoor O_3 levels might indicate more polluted outdoor air, including increased levels of precursors for secondary PM, which can infiltrate and increase indoor levels. In contrast, indoor PM_{10} showed a weak correlation with indoor CO_2 (0.35), indicating that the increase in particulate matter concentrations is not strongly linked to the CO_2 source. This weak correlation suggests that external environmental factors may have a greater influence on indoor particulate matter levels, or that even with a relatively small number of people, significant increases in particle concentrations could result from factors like outdoor air infiltration or resuspension from indoor sources.

Several other strong correlations were identified, including those between indoor CO_2 and indoor temperature (0.87), indoor CO_2 and outdoor temperature (0.79), indoor temperature and outdoor ozone (0.71), and between indoor and outdoor temperatures (0.85). These correlations are likely influenced by daily cycles, with rising temperatures in the morning as the store opens, leading to increased CO_2 levels due to human activity and the formation of ozone.

Indoor PM_{10} also displayed moderate positive correlations with indoor temperature (0.40), outdoor PM_{10} (0.43), outdoor ozone (0.54), and outdoor temperature (0.43). This further emphasises the role of external environmental factors on indoor particulate concentrations. Warmer conditions promote the resuspension and transport of particulates, while the moderate correlation with outdoor PM_{10} suggests that infiltration plays a significant role in indoor air quality.

To facilitate the visualisation of relationships between variables, a correlation-based dendrogram was constructed (Fig. S3 – supplementary material). The dendrogram reveals three distinct clusters at a 70% similarity threshold. The first cluster comprises PM_{10} In, CO_2 In, T In, T Out, O_3 Out, solar radiation (SolRad), and wind speed (WindS). This suggests that these variables are closely related, likely reflecting the influence of weather conditions and outdoor air quality on indoor particulate levels and CO_2 concentrations. The second cluster consists of TVOC In and CO In, suggesting a relationship between these indoor pollutants that may be linked to indoor sources or shared external influences. The third cluster groups RH In, RH Out, NO_X Out, and PM_{10} Out. This indicates that relative humidity and nitrogen oxides, along with outdoor particulate matter, are correlated, likely driven by external atmospheric conditions and emissions, primarily related to vehicular emissions.

3.4. Elemental concentrations and enrichment factors

A total of 15 elements were analysed, but the presence of only 13 was confirmed: Ca, Fe, K, S, Cl, Ti, Zn Mn Ni, Cr, V, Cu, Br. Fig. 3 categorises these elements into major elements (concentrations >50 ng/m^3) and minor elements (concentrations <50 ng/m^3), ranking them from the highest to the lowest indoor concentrations. The outdoor concentrations were consistently higher than the indoor values.

To better understand the sources of these elements, enrichment factors (EFs) and pollution ranges were plotted in Fig. 4. Although the highest concentrations of metals were found outdoors, the highest enrichment factors were observed indoors for S, Cl, Zn and Ni. Outdoor and indoor S exhibited a strong Spearman correlation of 0.71. An average indoor-to-outdoor ratio (I/O) of 0.21 was obtained for this element. Cl, which is grouped in the same enrichment class as S, had an I/O ratio of 0.83 and a correlation of 0.60 with outdoor concentrations. As the store has an HVAC system filtering the air, these indoor and outdoor concentrations and EF values suggest not only an influence of external pollution but also indoor sources. The use of chlorinated cleaning products was observed in the store, which is likely a significant source of this element. Zn exhibited the highest EF, making it the only element classified as "extremely enriched" indoors. Its strong correlation with outdoor Zn (r = 0.87) suggests that outdoor pollution significantly contributes to its presence indoors. Recent studies indicate that PM_{10}-bound Zn is a tracer of tyre wear in urban environments (Harrison and Alghamdi, 2023). Many cosmetics, sunscreens, and lotions also contain zinc oxide, which can contribute to its indoor levels. Despite its low concentrations, Ni was classified as very high enriched. It was present at an average I/O ratio of 0.77. Both Zn and Ni are often used in dyes and finishes for fabrics, as well as in metal components like zippers, buttons, and snaps. Certain cleaning agents could also contribute to indoor Ni and Zn levels. Some materials used in construction may contain these two metals, which can be released into the air over time. Nickel can be present in dust and particulate matter from outdoor sources, such as vehicle emissions, which may be brought indoors. Certain electronic devices and their components may also contain Ni and Zn, potentially contributing to indoor exposure.

3.5. Health risk analysis

The target cancer risk (CR) is set at 1×10^{-6}, while the target hazard quotient (HQ) is established at 1. None of the elements analysed in this study approached the HQ threshold, indicating that these elements pose no significant risk (Table 1). Therefore, carcinogenic effects associated with them are unlikely to manifest. As observed by Alves et al. (2020) in a study in a university cafeteria, Cl, Mn and Ni exhibited the highest HQ, indicating that these are among the most common hazardous elements in indoor environments.

The combined value for the elements analysed in this study - vanadium (V), chromium (Cr), and nickel (Ni) - was 5.50×10^{-9}, significantly below the target cancer risk limit of 1×10^{-6}. It is important to note, however, that this assessment includes only the analysed elements; other unmonitored components could also contribute to the overall carcinogenic risk.

3.6. Volatile organic compounds

The concentrations of VOCs analysed, are displayed in Table 2. Limonene exhibited the highest I/O ratio. The indoor concentration of limonene was 833 times greater than the outdoor level, indicating

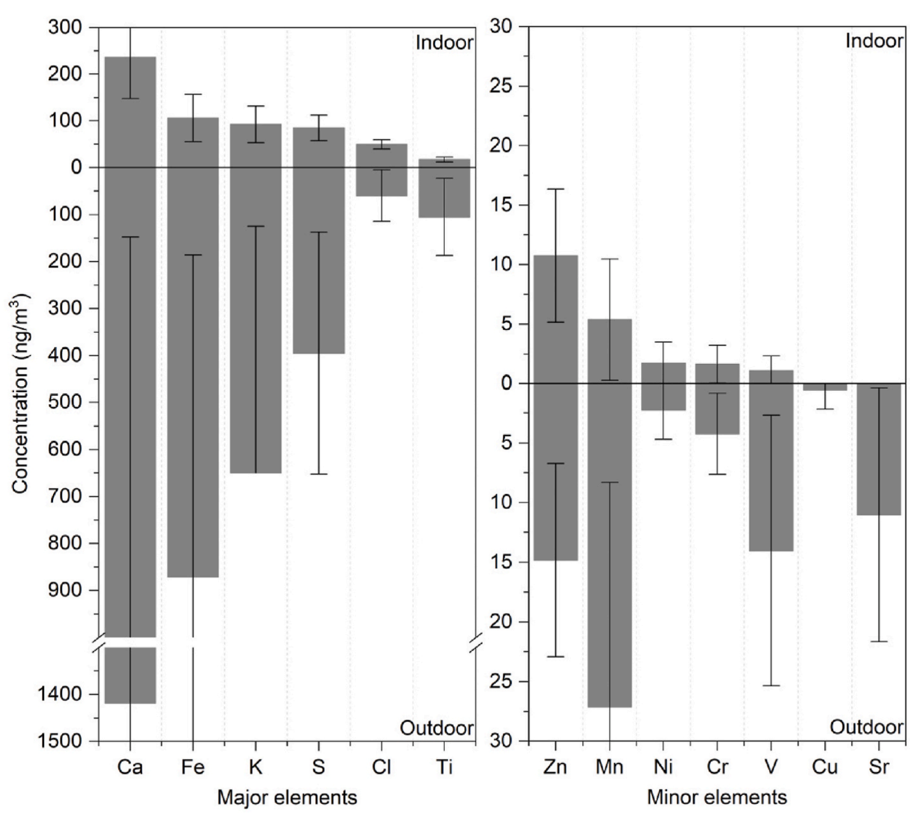

Fig. 3. Indoor and outdoor element concentrations during occupancy periods. The graph on the left shows the major elements (concentrations >50 ng/m^3) and the graph on the right shows minor elements (concentrations <50 ng/m^3).

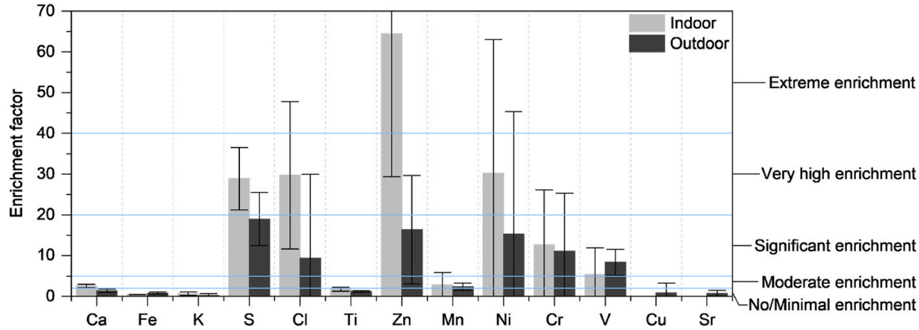

Fig. 4. Enrichment factors and classes of pollution.

Table 1
Hazard quotient from inhalation exposure to noncarcinogenic PM_{10}-bound elements.

HQ	Cl	V	Cr	Mn	Fe	Ni	Zn	Total
Average	7.19×10^{-2}	5.80×10^{-2}	7.30×10^{-4}	2.27×10^{-2}	9.95×10^{-6}	2.33×10^{-2}	2.36×10^{-6}	1.77×10^{-1}
Max	1.04×10^{-12}	1.61×10^{-1}	1.94×10^{-3}	5.49×10^{-2}	1.82×10^{-5}	6.74×10^{-2}	5.00×10^{-6}	3.89×10^{-1}
Min	5.55×10^{-2}	*	*	*	4.11×10^{-6}	*	*	5.55×10^{-2}

*Concentrations below the detection limit.

Table 2
Concentrations of volatile organic compounds, including carbonyls, in different clothing types, and average indoor/outdoor ratios.

VOC (μg/m^3)	Men's and women's clothing section	Children's clothing section	Outdoors	Average I/O
Acetic aldehyde	11.2	11.6	0.8	14.2
Acrolein	<0.27	<0.27	<0.19	–
Benzaldehyde	0.84	0.96	0.15	6
Benzene	0.13	0.13	0.2	0.65
Butanal	<0.9	<0.9	<0.6	–
1,4-Dichlorobenzene	<0.027	<0.027	<0.019	–
Ethylbenzene	0.76	0.81	0.38	2.07
Formaldehyde	10	10.1	1.4	7.18
Hexanal	13.7	13.4	0.7	19.4
Isopentanal	<0.2	<0.2	0.3	0.67
Limonene	27	28	0.033	833
Naphthalene	0.33	0.3	0.042	7.5
α-Pinene	14	15	0.066	220
Pentanal	2.2	2.2	<0.3	7.33
Propanal	2.2	2.3	0.4	5.63
Styrene	0.55	0.61	0.078	7.44
Tetrachloroethylene	120	130	1.6	78.1
Toluene	1.5	3.4	0.58	4.22
Trichloroethylene	0.044	0.044	<0.016	2.75
mp-Xylene	2.4	2.6	1.3	1.92
o-Xylene	1.2	1.3	0.6	2.08

*I/O ratio considering the detection limit.

significant indoor sources. Limonene does not have many limits set for workplace, however the International Labour Organisation and World Health Organisation (ILO-WHO, 2021) have set a maximum workplace concentration (MAK) of 28 mg/m^3 (5 ppm). This limit was far from being exceeded. Many commercial cleaning agents, especially those marketed as eco-friendly or citrus-scented, contain limonene as a key ingredient. Some fabrics may be treated with limonene-based finishes or chemical agents during manufacturing to impart fragrance or provide antimicrobial properties. Also, fabric softeners, laundry detergents, and dryer sheets often contain limonene for scent enhancement. Packaging for certain clothing items, particularly those with a citrus scent, may contain limonene or be made from materials that emit it. Some natural materials, like wood or certain resins used in store fixtures or decor, may also emit limonene. The values observed in this study are significantly higher than those reported by Kim et al. (2024), who recorded an average limonene concentration of 2.0 μg/m^3 in clothing shops located in an underground shopping centre in Korea. Other study by Robert et al. (2021) found an average limonene concentration of 31.9 μg/m^3 in clothing stores, similar to the levels found in the present study. Limonene is considered to have low toxicity (Kim et al., 2013). However, at elevated concentrations, it has been associated with respiratory issues, including asthma (Dales and Cakmak, 2019). Evidence also suggests that limonene can have more pronounced health effects when it reacts with other pollutants, forming secondary organic aerosols (Rösch et al., 2017), which may result in inflammatory processes greater than the limonene alone (Anderson et al., 2013). This shows the importance of further research to better understand the health impacts of limonene.

α-Pinene exhibited an I/O ratio of 220, also suggesting strong indoor sources. Fabrics made from natural fibres, such as cotton, linen, and wool, may have trace amounts of α-pinene. In addition, some fabrics may be treated with natural preservatives or antimicrobial agents that contain this VOC. Wooden furniture, shelves, or display cases, also emit α-pinene, particularly if they are made of coniferous trees like pine. The concentration of α-pinene observed in this study closely matches the findings of Robert et al. (2021), who reported an average concentration of 10 μg/m^3 in clothing stores. Similar to limonene, α-pinene, has very low toxicity, and also has been associated with inflammatory responses when forming secondary organic aerosols (Khan et al., 2021), which, in some cases, lead to respiratory irritation (Rohr, 2013). Both limonene and α-pinene are recognised as common indoor monoterpenes (Król et al., 2014). Monitoring these VOCs is crucial for identifying sources and assessing the effectiveness of indoor ventilation systems, as poor ventilation can lead to the accumulation of these and other VOCs (Pereira et al., 2008).

Tetrachloroethylene displayed the third highest I/O ratio (78.1). The Scientific Committee on Occupational Exposure Limits (SCOEL) sets an 8-h exposure limit of 138 mg/m^3 and a short-term (15-min) exposure limit of 275 mg/m^3, both far above the average concentration of 125 μg/m^3 observed in this study. However, the measured concentrations were significantly higher than those reported in similar studies. Kim et al. (2024) recorded an average tetrachloroethylene concentration of 0.6 μg/m^3 in a similar environment. Robert et al. (2021) reported a value of 1.6 μg/m^3 in a clothing store. These differences emphasise that specific indoor conditions, such as ventilation or local pollution sources, can significantly affect VOC concentrations. Tetrachloroethylene is a chemical commonly used in dry cleaning. As noted in the store description, a laundry offering both wet and dry cleaning is located in the same building, which may contribute to elevated levels of this pollutant within the premises. In contrast, formaldehyde concentrations were notably lower compared to other studies. For instance, Kim et al. (2024) reported formaldehyde levels of 33.5 $\mu g/m^3$ in similar retail settings, while Robert et al. (2021) measured concentrations around 22 $\mu g/m^3$. The SCOEL sets an 8-h time average exposure limit for formaldehyde at 369 $\mu g/m^3$, while the short-term exposure limit is 738 $\mu g/m^3$. Both thresholds are considerably higher than the values observed in this study. However, the WHO, in its guidelines for indoor air quality, has proposed a more stringent short-term exposure limit of 100 $\mu g/m^3$ over 30 min.

3.7. Microorganisms and settleable dust

The store exhibited an average dust deposition rate of 6.43 $mg/m^2/day$, while the warehouse showed a similar average rate of 6.32 $mg/m^2/day$. Although a higher deposition rate might be expected in the warehouse, the similarity between the environments is likely due to lower foot traffic and to the fact that replacement of clothes does not occur frequently. According to a German regulation (Bundesregierung, 2021), the deposition limit for non-hazardous dust is set at 350 $mg/m^2/day$ on an annual basis, which is significantly higher than the values observed in this study. Overall, deposition rates across the various sampling points showed minimal variation (Fig. S4 – supplementary material).

Fungal concentrations on MEA, DG18, and DG18 incubated at 37 °C media are presented in Table 3. On MEA, *Trichoderma* sp. was the predominant genera, whereas *Penicillium* sp. dominated on both DG18 and DG18 37 °C. However, it was possible to identify *Aspergillus* sections with toxigenic potential (*Nigri*) (Leong et al., 2006) and with clinical relevance (*Fumigati*) (WHO, 2022). In addition, *Fusarium* sp. are classified by the WHO (2022) as belonging to the high risk group of fungi due their ability to cause fusariosis, which can be a life-threatening disease, being inherently resistant to most antifungal agents. Concerning *Aspergillus* section *Fumigati,* WHO ranked it in the critical group, since azole-resistant invasive aspergillosis is a life-threatening disease presenting very high mortality (WHO, 2022). This section has also been proposed has a surrogate of harmful fungal contamination in specific occupational environments (Marchand et al., 2024; Viegas et al., 2023, 2022).

Bacterial concentrations for each store section, along with deposition rates, are shown in Fig. S4 in the supplementary material. The results indicate generally low bacterial levels, with the highest concentration recorded in the women's clothing section at 13.1 $CFU/m^2/day$. These values are considerably lower than those found in a study on second-hand clothing shops in Thailand (Reanprayoon and Yoonaiwong, 2012), where similar sampling was used but different culture media - blood agar, MacConkey, and sabourand dextrose agar - to quantify Gram-positive bacteria, Gram-negative bacteria, and microfungi. The reported bacterial concentrations in the Thailand study, converted to $CFU/m^2/day$, were 3951 $CFU/m^2/day$ for Gram-positive bacteria, 1303 $CFU/m^2/day$ for Gram-negative bacteria, and 2197 $CFU/m^2/day$ for microfungi. This strong difference suggests that used clothing has a significantly higher microbial load compared to new clothing. Several factors likely contribute to these differences. During manufacturing, various processes and agents serve as biocides that reduce microbial load on new fabrics. These include high-temperature treatments, industrial detergents, and the application of antimicrobial agents (Benninger, 2016). Also, heat exposure during textile production can denature proteins and disrupt cellular structures in microorganisms, while detergents and biocides may inhibit bacterial growth by disrupting cell walls. After the sale, factors such as washing frequency, water temperature, and detergent use significantly impact microbial load (Abney et al., 2021).

4. Conclusions

A comprehensive study of indoor air quality in a clothing store was conducted at one of the largest franchises in Portugal to address the gap in research regarding these environments. Simultaneous indoor and outdoor monitoring of both gaseous and particulate pollutants was carried out. The concentrations of PM_{10} and volatile organic compounds remained below critical thresholds for health risks. However, outdoor pollution significantly contributed to the indoor environment, with approximately 69% of indoor PM_{10} originating from external sources. Indoor PM_{10} concentrations were lower than those measured outdoors. Although the store has an HVAC system to control the indoor temperature throughout the year, the study region is characterised by a large variation in temperature between the coldest and hottest months, which can lead to different activity patterns. For a more comprehensive understanding of indoor air quality in the store, future research would benefit from conducting monitoring across different seasons. Additionally, using personal monitors would provide a more accurate estimate of the PM exposure levels inhaled within the store, providing a better estimation of health risks associated with airborne particles in these spaces.

Indoor concentrations of limonene and α-pinene were much higher than outdoor levels, suggesting the presence of indoor sources, likely

Table 3
Fungi species on different culture media for the different sections of the clothing store.

Section	MEA	$CFU/m^2/day$	DG18	$CFU/m^2/day$	DG18 37 °C	$CFU/m^2/day$
Kids					*Penicillium* sp.	1.87
Woman			*Penicillium* sp.	2.8	*Penicillium* sp.	0.93
			F. graminearum	0.93		
					Aspergillus section *Nigri*	0.93
Home textiles	*Alternaria* sp.	0.93				
			Aspergillus section *Fumigati*	0.93		
	F. graminearum	0.93				
	Aspergillus section *Nigri*	0.93				
			Penicillium sp.	0.93	*Penicillium* sp.	0.93
			Trichoderma sp.	0.93		
Winter coats			*Penicillium* sp.	0.93		
	Trichoderma sp.	1.87				
Man	*Aspergillus* section *Nigri*	0.93				
	Paecilomyces sp.	0.93				
Storage					*Aspergillus* section *Nigri*	1.14
	Trichoderma sp.	2.28				

MEA: malt extract agar DG18: dichloran glycerol DG18 37 °C: dichloran glycerol incubation at 37 °C.

from fabrics, furniture, and cleaning agents. The concentrations of elements such as vanadium, chromium, and nickel were well below the thresholds for carcinogenic risks and hazard quotients, indicating no chronic health risks. However, other unmonitored pollutants could still pose risks. The store showed an adequate ventilation during both open and closed hours, meeting the minimum standards recommended by the ASHRAE. However, the infiltration of outdoor air pollutants remains a concern, as evidenced by the significant presence of particulate matter and elements originating from outdoor sources. Low concentrations of microorganisms and deposition rates were found. However, fungal species with clinical and toxigenic potential were detected. For future studies, it would be interesting to assess the microbial load in new clothes, made from different textiles, to compare with second-hand clothes.

Overall, the indoor air quality is within safe limits, with strong influence of outdoor pollution, particularly particulate matter. This suggests a need for improved filtration or ventilation strategies to reduce the impact of external sources.

CRediT authorship contribution statement

Leonardo Furst: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yago Cipoli:** Writing – review & editing, Methodology. **Nuria Galindo:** Writing – review & editing, Resources, Methodology. **Eduardo Yubero:** Writing – review & editing, Resources, Methodology. **Carla Viegas:** Writing – review & editing, Resources, Methodology, Funding acquisition. **Bianca Gomes:** Writing – review & editing, Methodology. **Renata Cervantes:** Writing – review & editing, Resources. **Teresa Nunes:** Writing – review & editing, Resources, Methodology. **Manuel Feliciano:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Célia Alves:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.125836.

Data availability

Data will be made available on request.

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