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Metrics on Perception, Concentration and Characterization of Indoor Air Quality in a University Library

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ABSTRACT HEADING

A longitudinal study was conducted to establish metrics on perception, concentration and characterization of indoor air quality (IAQ) at a university library building. A questionnaire was applied to library staff in 2016 and 2017 to measure perceived indoor air quality (PIAQ) and perceived respiratory health impacts (PRHI). Measurements of $PM_{2.5\text{-}10}$ and $PM_{2.5}$ concentration levels were made in 2017 and 2019, respectively. Characterization through morphology and elemental composition of particulate matter (PM) samples were obtained through scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDS). PIAQ metrics indicated eye and throat irritation, the presence of PM and biological compounds as determinants of IAQ. The library is perceived as a sick building and the indoor air is perceived as polluted. PRHI metrics indicated that respondents consider they have good respiratory health. Average $PM_{2.5}$-24h was 3.67 $\mu g.m^{-3}$ (95% CI: 1.58, 6.87), values well below international health-based recommendations. SEM-EDS analysis indicates that biogenic aerosols and mineral dust particles were dominant in 2017 and 2019 samples and that there is an influence of indoor and outdoor sources. PM was influenced by furniture, specific library activities and outside air delivered by the ventilation system, as well as through open windows. It is recommended that future studies consider other pollutants like formaldehyde and ozone.

INTRODUCTION

Indoor air quality (IAQ) refers to the control of the quality of air inside enclosed spaces (buildings, tunnels, etc) in order to ensure healthy and clean conditions for the public in general (Heinsohn and Cimbala, 2003). Perceived indoor air quality (PIAQ) has been used as the basis for several ventilation standards and is used to assess indoor odours and air quality in buildings (Jones, 2017). Surveys and questionnaires have been used to measure PIAQ in library buildings (Wu et al., 2018), hospital buildings (Tähtinen et al., 2018), households (Le et al., 2014) and schools (Finell et al., 2018). Furthermore, studies on the perception of indoor air quality have also been conducted for self-reported health and comfort in office buildings (Roulet et al., 2005, 2006; Bluyssen et al., 2011, 2016; Sakellaris et al., 2016; Kim and Bluyssen, 2020).

Surveys and questionnaires can be designed specifically for the study or be based on previous similar work. Studies on PIAQ may study several pollutants, but more often or not, criteria pollutants are always within the scope of each study, particulate matter (PM) being of interest. PM is a worldwide air pollution reference. PM can be classified based on equivalent aerodynamic diameter in PM_{10} ($\leq$ 10μm), $PM_{2.5}$ ($\leq$ 2.5 μm, fine fraction), $PM_{10\text{-}2.5}$ (PM 10- 2.5 μm, coarse fraction or respirable fraction) (Seinfeld and Pandis, 2016). Scanning electron microscopy coupled with an energy dispersive spectroscopy (SEM-EDX) of $PM_{2.5}$ samples has shown that this size comprehend a wide range of particle types, including biogenic aerosols and mineral dust (Hu et al., 2012, Sahu et al., 2018). Perception of pollution and PM concentrations are well-established metrics of IAQ. SEM-EDX of PM_{indoor} samples have been used in previous research but have not been presented as metrics of IAQ. An air quality metric should identify when the quality of indoor air is unacceptable and should be based on its effects on human health and comfort, acknowledging that they may not be immediate (Jones, 2017). The aim of this study is to evaluate indoor air quality in a university library through a

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longitudinal study covering metrics on perception, concentration and characterization of particulate matter.

UNIVERSITY LIBRARY DESCRIPTION

The Library building (four floors and a basement) is one of 78 buildings on the university campus of the Simon Bolivar University, located in the Sartenejas Valley, Caracas, Venezuela. The building holds a collection of ~300,000 bibliographic and hemerographic volumes. The library's authorities have stated that since 2016, the building started ever-increasing operational difficulties, including limiting personnel working hours and cleaning schedules, resulting in library workers beginning to express discomfort with their indoor environment, according to an internal report. Since August 2018, the air conditioning of the library building (for the control of the indoor air temperature, <21 ° C; and relative humidity, <65%) ceased to be operational, and a change toward natural ventilation was made. Higher temperatures and relative humidity have been recorded ever since, along with a gradual deterioration of the collection and the indoor environment. In 2019, maintenance and cleaning activities were carried out that comprised the removal of 6,000 m^2 of carpet on three floors of the library.

METHODS

Indoor air quality perceptions questionnaire

A perception of indoor air quality and respiratory health questionnaire was used, which is based on that of Morantes et al. (2020) for outdoor air. It was adapted to an indoor air context. The questionnaire was applied to library staff in July and August 2016 and in August and September 2017. The first section of the questionnaire measures an occupant's perception of air quality (PIAQ) and the second addresses perceived respiratory health impacts (PRHI). Table 1 gives the questions of both sections. Responses for A1-A5 are treated as metrics accounting for the frequency of responses for each option. A6-A7 and B1-B2 metrics are the numerical value assigned to each option. For A6 and A7, higher values are related to more optimistic scenarios; B1 and B2 are the opposite.

PM sampling

Two PM collection campaigns were carried out (Oct.Nov-2017 and Oct.Nov-2019). The first campaign was carried out with the library under regular operation. The second when the library was not in operation, due to maintenance activities. October and November 2017 sampling: $PM_{2.5}$- PM_{10} ($PM_{(2.5\text{-}10)indoor}$) was sampled in two working offices. In each place, 9 samples were taken giving a total of 18. The arrangement consisted of a low flow pump (2.5 $L.min^{-1}$), an aluminium cyclone cassette sampler (SKC) for breathable dust (cutoff point ~4 μm) and a 47 mm fibreglass filter (borosilicate glass) (COVENIN 2252:1998, INSHT, 2011). Due to problems with the precision of the available balance (0.1 mg), PM was obtained only for analysis by electron microscopy. October and November 2019 sampling: $PM_{2.5}$ was sampled on two floors: 12 samples were taken total. Samples were collected for sampling periods of 48 h (Mon-Wed; Wed-Fri; Sat-Sun). A Dichotomous Ambient Sampler (15.0 $L.min^{-2}$) with PTFE membrane filters of 46.2 mm was used.

Scanning electron microscopy

Scanning Electron Microscopy (SEM) coupled with an energy dispersive spectroscopy (EDX) was performed on the 2017 and 2019 PM samples. SEM-EDX analysis provides data on particle morphology and elemental composition (%weight). Microscope magnifications of 0.5, 1, 2, 5, 10, 20, 50 μm were used. The EDS spectra of the Teflon blank filter was measured and subtracted from the samples (approximate 1C:2F ratio). Borosilicate filters are mainly made up of Si and B, although they may have traces of other elements (Ca, Na, Al, Cl, K, Cu, Ba, Zn). SEM-EDS of a blank filter was used to contrast the elemental composition particle by particle. PM characterization is interpreted as a qualitative metric by associating the results with possible sources of contaminants (indoor/outdoor). Plausible particle types and sources are obtained (1) based on elements present in X-ray spectra, (2) based on % weight of elements and the highest peaks in X-ray spectrum, (3), accounting for morphology and (4) using clustering rules; the latter were assigned according to results in previous research (Pachauri et al., 2013, Hu et al., 2012).

RESULTS

13% of library workers answered the questionnaire in July and August 2016 and 49% in August and September 2017. Figure 1 shows the percentage of options selected in the multiple-choice questions (A1-A5). It shows that respondents selected, on average less than 30% of the options offered. In incidences (A1) in 2017, they selected 4 of the 5 options (80%), eye and throat irritation are the most common incidents. Poor indoor air quality was related to furniture (A2). In diseases (A3) they selected, on average, 6 of the 9 options (66%), and mainly selected respiratory allergies and eye and throat irritation as diseases. Biological contaminants and particles were the most voted for pollutants (A4). Regarding improvement actions (A5), some respondents voted for 4 of the 5 options, although the average does not exceed more than 2. Through their answers, the respondents declare that they perceive several determinants of IAQ. In both years, the majority of respondents declared perception of PM pollution. Given that the relations between perceived indoor environment depend on the socio-cultural context, as well as personal and building characteristics (Sakellaris et al., 2016; Kim and Bluyssen, 2020), the variability in responses may be due to psychosocial factors that affect their PIAQ (Finell et al., 2018), personal parameters (Langer et al., 2017) and the specific location of the occupant within the library (Wu et al., 2018). These factors are outside the scope of this study.

Table 1. Perception metric details.

Metric	Perception of air quality				
Question	A1.Perception of <u>incidents</u> due to poor indoor air quality	A2.Perception of <u>causes</u> of emission of indoor air pollutants	A3.Perception of respiratory/cardiac <u>diseases</u>.	A4.Perception of the presence of indoor <u>pollutants</u>	A5.<u>Actions</u> to be taken to improve indoor air quality
Choices (Multiple choices)	1. Difficulty breathing 2. Eye irritation 3. Smoke presence 4. Unpleasant odours 5.. Sore throat	1. Introduced outside air 2. Deposit of materials 3. Construction materials 4. Furniture 5. Use of chemicals 6. Air conditioning 7. Supplies (toner, solvents, disinfectants)	1. Choking 2. Cough 3. Respiratory allergies 4. Asthma 5. Lung diseases 6. Eye / throat irritation 7. Bronchitis 8. Lower respiratory tract infections 9. Cancer	1. Carbon monoxide 2. VOCs 3. PM 4. Biological contaminants 5. Radon 6. Chemicals	1. Contribute a fee to improve the air circulation system 2. Promote the prohibition of the use of chemical substances 3. Contribute to creating indoor air awareness guide 4. Change job 5. Periodically clean workplace

Metric	Perception of air quality		Perceived respiratory health impacts	
Question	A6. Do you think the air you breathe here is polluted?	A7. Do you think that your workplace could be attributed to the category of sick building?	B1.Do you think that air pollution from your work has negatively affected your respiratory health?	B2.How is your respiratory health?
Choices (Single choice)	1. Definitely yes 2. Probably yes 3. Probably no 4. Definitely no	1. Definitely yes 2. Probably yes 3. Probably no 4. Definitely no	1. Definitely no 2. Probably no 3. Probably yes 4. Definitely yes	1. Very Good 2. Good 3. Bad 4. Very Bad

Fig 2 shows the results on the perception of the respondents regarding indoor air pollution and the decision to classify the workplace as a *sick building*. The perception stated in both questions was to affirm that the air is polluted and that there is a sick building. There is an increase in the affirmative responses towards 2017, which could indicate that the respondents perceived deterioration in the workplace. This was expected as the library reports continuous deterioration of the working environment, dating back to 2016 when the maintenance of the building decreased, limiting personnel working hours that reduced cleaning schedules. In 2017, the situation worsened by not renewing the bulbs that were damaged and increasing the space illumination deficiencies, bathroom water leakages resulting in odour issues, electricity shortages at the local level, and limited use of the library professional vacuum cleaners.

Fig. 3 shows the results related to respiratory health perceptions for 2016 and 2017. Regarding the declaration of having been affected by pollution in 2016 (Fig. 3 a), the affirmative and negative responses were approximately equivalent with 57% positive and 43% negative. In 2017, the responses indicating that indoor air has not negatively affected their health increased to 72%. Interestingly, respondents perceive themselves as little vulnerable to indoor air pollution: they perceived deterioration in indoor air (Fig. 2 a) but it was not perceived as a major respiratory health issue.

It has been established that building, social and personal factors as well as the specific location within the building when surveyed, all can influence one's perceived health in a building (Bluyssen et al., 2011; Kim and Bluyssen, 2020).

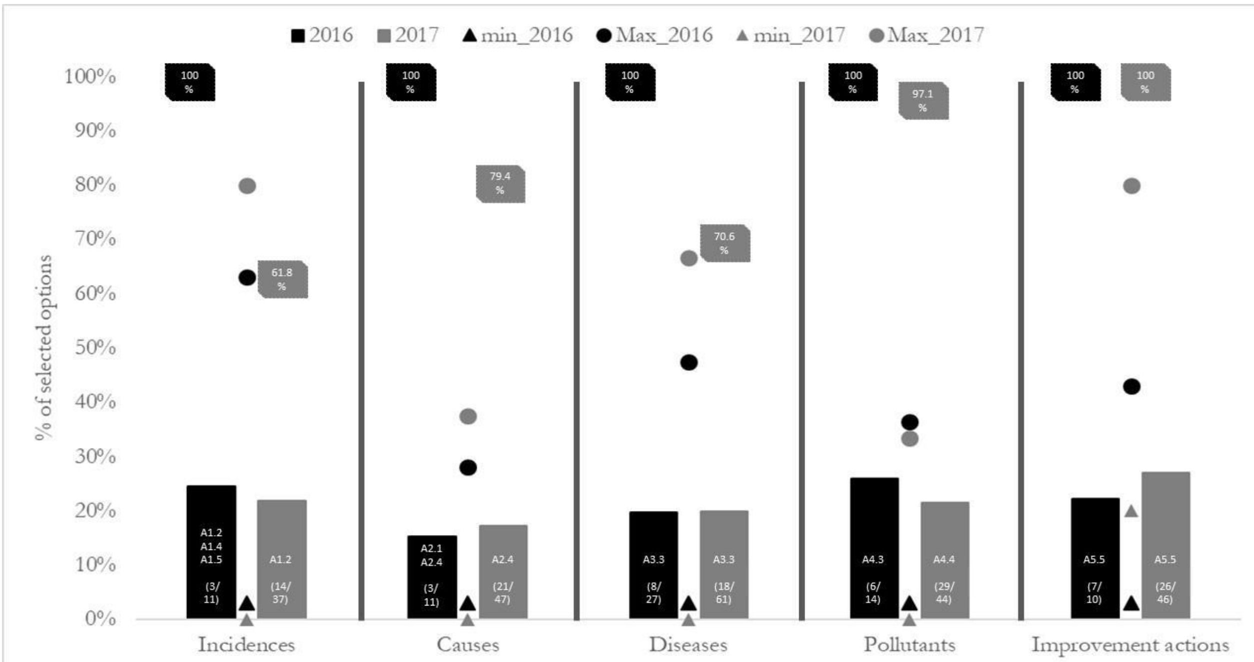

Figure 1 Perception of indoor air quality: percentage of options selected, questions A1-A5.

Note Fig.1. The most selected options are shown within the columns, See table 1. In parenthesis is the quantity of times that the option was selected over the total of selections. The boxes above the columns present the percentage of people that selected at least one option.

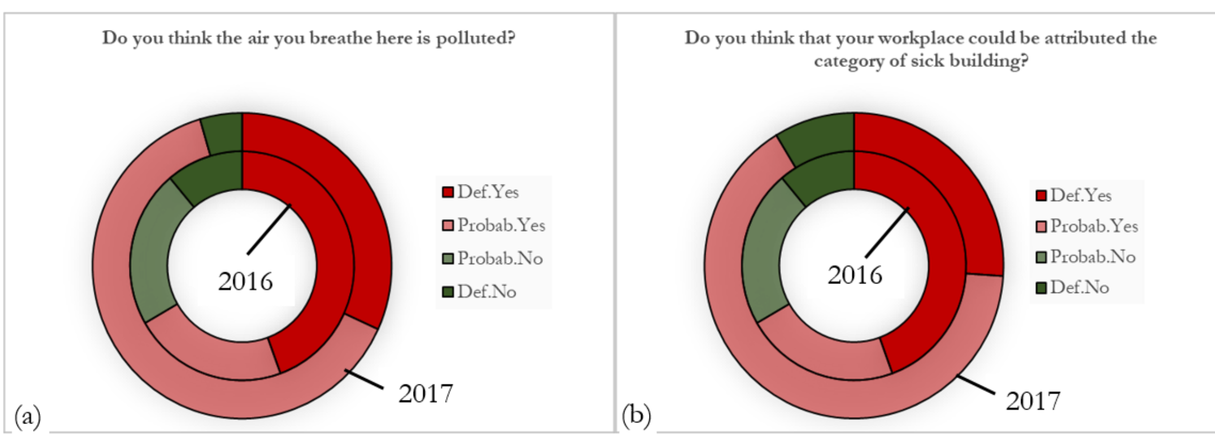

Figure 2 Perceived indoor air quality. (a) Perception of indoor air pollution. (b) Sick building attribution.

Venezuela has been experiencing an increasing socioeconomic crisis since the last decade, which has been affecting all social classes in the country, which has decreased the quality of life of the population (OAS, 2018). Under this reality, library workers may not perceive acute respiratory health symptoms as an urgent matter when there are other concerns related to subsistence living. As a result, self-reported respiratory health status may be perceived as not as important when considering other, more pressing matters. Somewhat counter-intuitive relationships between perceived IAQ and self-reported status have also been reported by Diaz et al. (2008) and Le et al. (2014).

In both years, the respondents declare they have good respiratory health (Fig. 3 b). When analyzing the surveys in detail, it was found that in 2016, the population that indicated that their respiratory health had been affected by air quality (17%), was the same size as that which reported negative respiratory health states. All four perception questions showed a change in respondents' responses between 2016 and 2017, indicating a change in perceived IAQ over time. Finell et al., (2018) also found significant differences among the years when the questionnaire was applied.

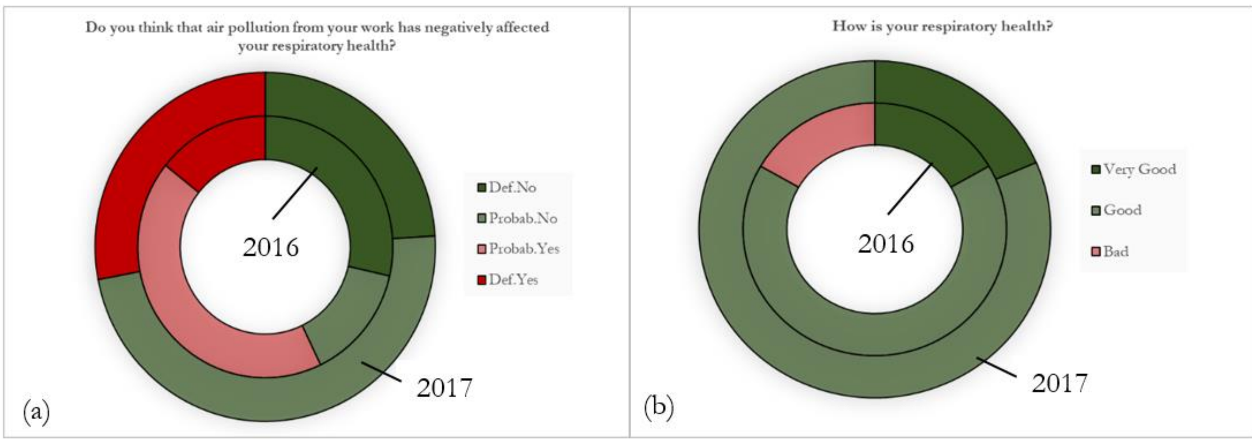

Figure 3 Perceived respiratory health impacts. (a) Health related negative effects perception. (b) Self-declaration of respiratory health.

Average concentrations of $PM_{2.5}$-24h for October and November 2019 sampling was 3.67 μg.m^{-3} (95% CI: 1.58, 6.87). The samples taken on weekends showed the lowest concentrations, tending to zero (an absence of personnel and closed windows). Personal activities have been shown to alter $PM_{2.5}$ concentrations (Zhang et al., 2017, Ramos et al., 2015). Higher concentrations coincided with carpet removal dates (Pearson correlation =0.694; $p<0.01$). PM concentration levels do not seem to be a cause for concern when compared to the $PM_{2.5}$-24h guideline value of 25 μg.m^{-3} proposed by WHO (2006). Although its composition should be evaluated to identify the type of aerosols (e.g. biogenic aerosols, presence of metals, etc) and their possible sources (indoor/outdoor).

Elemental composition and morphology allowed for the identification of four plausible groups of particle (Fig. 4). The relative abundance of each particle and possible sources are also shown. Biogenic aerosols (C + O ~90%wt) were present in both years, but more so in the 2019 sample. These aerosols include particles that are parts of insects, plants, skin and human hair, fragments of fungi, pollen, spores and microorganisms in general. These particles can come from indoor sources associated with mould and moisture, as the increase in indoor temperatures and relative humidity from 2018 could have favored the growth of mould and fungus indoors (WHO, 2009). This would explain the higher relative abundance of these biogenic aerosols in the 2019 sample. Pasquarella et al. (2015) also found biological aerosols (fungal spores) in a Palatine historical library in Parma, in the absence of visitors. Ca-rich (Ca >10 %wt) particles were found, possibly calcite ($CaCO_3$) and calcium oxides (CaO). Calcites in interior space may come from chalk used on library blackboards (Chithra and Nagendra, 2013, Sahu et al., 2018). These types of particles are also related to materials in the Earth's crust carried by air (Hu et al., 2012). Ca-rich particles were present in both samples but were predominant in 2017 when library blackboards were frequently used. By 2019, Ca particles are most likely to be a combination of previously deposited particles on the floor and by ventilation through open windows. Mineral dust particles (e.g. aluminosilicates and quartz) are particles composed mainly of Al-Si-Fe-O and other elements like Mg, Na, Fe or K whose origin is derived from soil dust resuspension and come from floor dust previously trapped in carpets and outdoor air (Pallarés et al., 2019). Metallic particles have concentrations >10%wt of metallic elements such as Fe and Cu. The presence of particles rich in Fe and Cu are associated with wear, caused by the use of metallic and metal-mechanical objects (Mugica-Álvarez et al., 2010) used on the large windows of campus buildings. They are also associated with the ingress of exterior dust from resuspension due to vehicular activity (brake wear, mechanical abrasion and lubricants of vehicles) (Pachauri et al., 2013).

Other particle types identified only in 2017 were salts (high Na particles). They can be caused by industrial fumes, biomass burning, sea salts and garbage combustion. High sodium particles with the presence of sulfur are associated with atmospheric reactions. The source of these particles is mostly associated with outdoor air. Its presence in the 2017 sample is related to outdoor ingress. Salt particles have been found to be present in outdoor air in the Sartenejas Valley (Rincon et al., 2019). The low concentrations of PM in indoor air suggest that PM is not a problem for indoor air quality.

The perception of those surveyed indicated that, although indoor pollution has not affected their health (Fig. 3 a), they do observe a deterioration of air quality in the years studied (Fig. 2 a) and associate it with particulate matter (See table 1, A3). PIAQ and perceived health does not always diagnose actual deficiencies in buildings (Roulet et al., 2005; Tähtinen et al., 2018) as many factors affecting IAQ may also affect PIAQ related to PM, including outdoor events (Oh et al., 2019) and outdoor PM concentrations (Wu et al., 2018).

Factors like high temperature and humidity can influence perceived air quality, as well as some health-related symptoms. Fang et al. (1998; 2004) reported that perception of air freshness, acceptability of air quality, the intensity of fatigue, headache and difficulty in thinking clearly, in an office space, can improve as occupants are exposed to slightly lower levels of air temperature and humidity. Moreover, He et al. (2017) studied the influence of temperature and humidity on perceived air quality, reporting that under moderate humidity conditions, the temperature did not significantly affect perceived air quality; this would show a higher impact of relative humidity than the temperature on perception. In our study, when applying the perception surveys (2016 and 2017), the library's air conditioning was operational, which ensured that the temperature and relative humidity remained <21 C and <65%, respectively. Therefore, we would expect that temperature and relative humidity did not influence respondents' perception of indoor air quality.

In this study, respondents indicated eye and throat irritation as the most common perceived incidence/illness, similar to that reported by Bluyssen et al., 2016. Gases like ozone (either with or without nitrogen dioxide) and unsaturated organic compounds (e.g. from citrus and pine oils) produce strong eye and airway irritation (Wolkoff and Nielsen, 2001). Indoor ozone can come from electrical devices (ozone generators, room air purifiers, photocopiers, laser printers) and/or disinfecting devices (in-duct air cleaners). Formaldehyde (a volatile organic compound), is known to be an irritant of the eyes and upper airways, especially the nasal cavity, and is suspected of causing allergic sensitization (WHO, 2010). Formaldehyde is released from various building materials: pressed wood products made with urea-formaldehyde resins or phenol-formaldehyde resins (Kelly et al., 1999), conversion varnishes (Howard et al., 1998), latex paints (Chang et al., 1999) and carpets (Hodgson et al., 1993). The sources of indoor ozone and formaldehyde described here could be encountered in the library building, and the presence of these materials might explain the respondent's perception of indoor air quality.

CONCLUSIONS

A longitudinal study was carried out to propose metrics related to indoor air quality in a university library. Perception metrics obtained in 2016 and 2017 indicated that library staff perceived polluted indoor air in the workplace, mostly labelling the building as sick. There was a notorious change of perception over the years with the general opinion changing towards declaring a deteriorating air quality. This was associated with the yearly growing building deterioration due to lack of maintenance. In parallel, from one year to the next, the workers declared to have good respiratory health. A change toward a better health status was attributed to a contextual country-level crisis.

Average $PM_{2.5}$-24h was 3.67 $\mu g.m^{-3}$ (95% CI: 1.58, 6.87), values were below international health-based recommendations. We can derive limited conclusions over the relations between perceived air quality and measured air quality: the questionnaires (2016 and 2017) and the sampling (2019) were done in different years, with very drastic different scenarios, shifting from an air-conditioned controlled building until in 2018, to a mostly natural ventilated building, without temperature and humidity control. The elemental composition and morphology of PM samples were used as metrics to identify plausible types of aerosols and sources. Biogenic aerosols and mineral dust particles were dominant in the 2017 and 2019 samples. The PM was influenced by the furniture, activities of the library and the outside air that infiltrated through the ventilation system and open windows. It is recommended that future studies should consider other pollutants that may be present, with special emphasis on formaldehyde and indoor ozone.

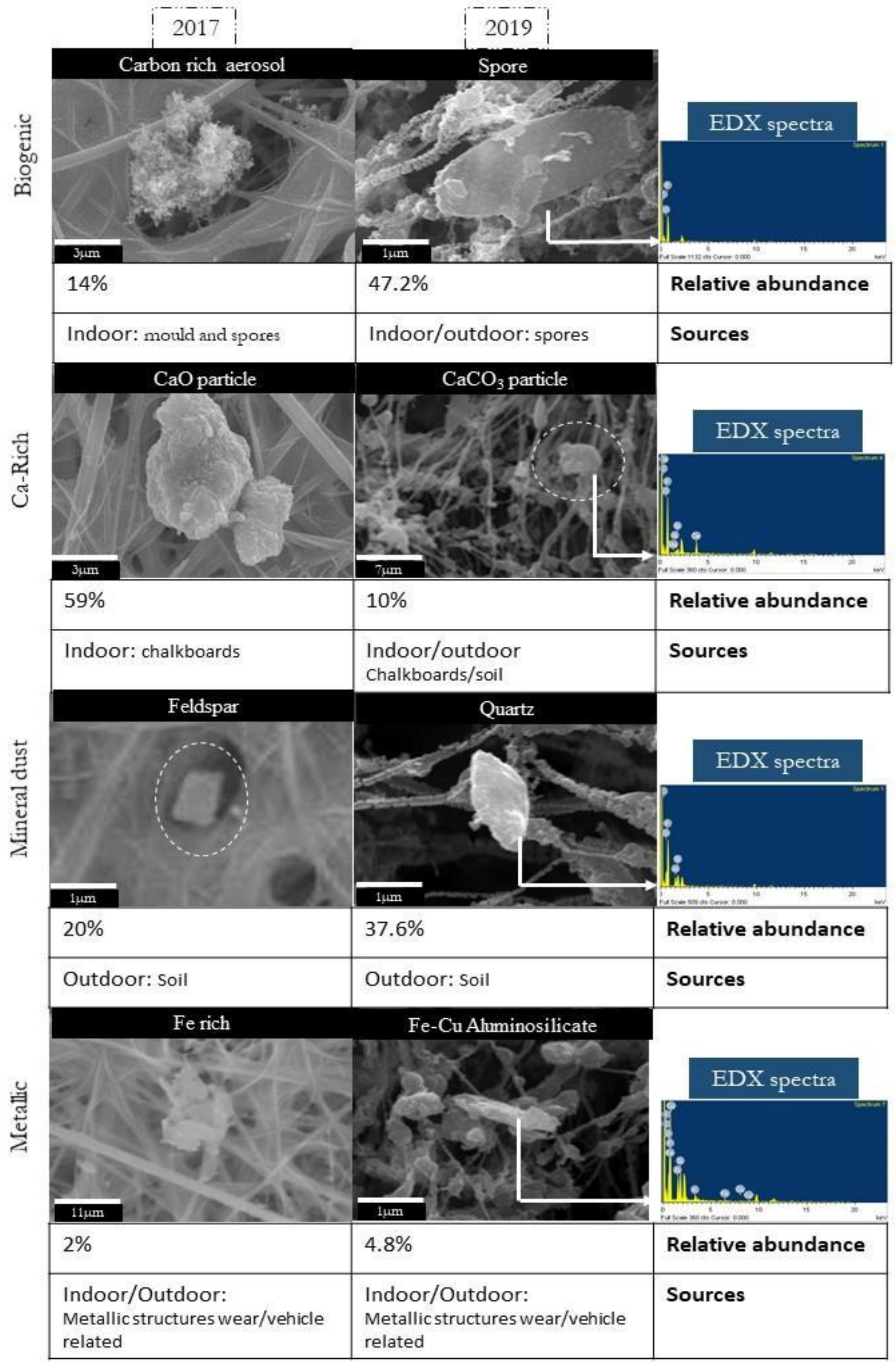

Figure 4 SEM photomicrographs for particle groups found in 2017 and 2019.

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