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Enhancing indoor air quality in office buildings: Insight from a field study

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Abstract. Building tight for minimizing building energy consumption and related carbon emissions might negatively affect indoor air quality (IAQ) if this is not correctly designed and evaluated during operation. To address this concern, a post occupancy evaluation study was conducted in a recent large office building in the Autonomous Province of Bolzano (Italy). The aim of the study was to collect evidence from a relevant case study and use it as a basis to define a standardized strategy for continuous monitoring of a larger portfolio of office buildings. Additionally, carbon dioxide (CO_2), particulate matter ($PM_{2.5}$, PM_{10}), total volatile organic compounds (TVOC), air temperature, and relative humidity were recorded 24/7 for a 5-week period in winter 2023. Detailed spot measurements of VOCs and aldehydes were also carried out. Perceived air quality (PAQ) was evaluated through satisfaction surveys which covered various factors influencing PAQ including 14 potential sources of dissatisfaction. A cross-modal approach allowed for a comprehensive examination of the different domains (thermal, visual, acoustic, and IAQ) on PAQ. Measured contaminants' levels were below recommended limits. Overall, participants were neither satisfied nor dissatisfied with PAQ, and possible related sources of dissatisfaction were elements such as the relative humidity. Sick building syndrome (SBS) self-reported symptoms such as dry skin and itchy eyes confirmed potentially too low relative humidity levels.

1 Introduction

Since the 1980s, there has been a growing understanding that indoor air quality (IAQ) significantly impacts well-being, productivity, and health [1]. This is especially true today as buildings are constructed with increased airtightness for energy-saving and efficiency purposes.

Organizations such as the World Health Organization (WHO) have proposed a list of pollutants and thresholds to be considered for acceptable IAQ [2]. These thresholds are set considering the potential harmful effects of air pollutants on health. However, good IAQ should not only ensure the health of occupants but also create sensations of comfort and pleasure, ultimately enhancing productivity. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines acceptable air quality as

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air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction (ASHRAE, 2022) [3].

Office buildings are a particularly sensitive category as people spend a significant amount of time in them, but as end-users, they often have limited control over ventilation and IAQ. This can lead to discomfort and higher energy consumption [4]. Various studies have focused on assessing IAQ in offices, addressing aspects such as perceived air quality (PAQ) [5], the relationship between IAQ and productivity, and sick building syndrome (SBS) [6], as well as the link between ventilation and energy consumption [7].

The measurement campaign discussed in this paper is part of the "BREATH – Air Quality and Health in Provincial Offices" project, funded in 2022 by the Autonomous Province of Bolzano and conducted by Eurac Research. The overall goal of the project is to assess and contribute to improving IAQ in office buildings managed by the Autonomous Province of Bolzano. The final aim is to define a protocol for assessing IAQ and its health effects, and subsequently apply this protocol to the 108 office buildings within the province. The protocol is developed based on the field study experience which is described in this paper.

2 Methodology

2.1 Case study

The chosen case study is a large 5-storey office building located in Bolzano, northern Italy. The building is situated in surroundings classified as urban environment with light traffic. The structure was built in 2018 and features a reinforced concrete structure, complemented by external insulation and double-glazed aluminium windows. The offices face either the exterior or the internal courtyards and are distributed in all four cardinal points. The office layout includes a central corridor from which the offices can be accessed. The corridor is mechanically ventilated, but ventilation rates and overall exact functioning are not completely clear.

Each office exhibits similar occupational characteristics, furniture, and architecture, with standard office furnishings such as monitors, desks, and chairs (Figure 1). Despite some exceptions with a higher number of occupants (3, 4, or 5 people), the average number of occupants per office is one or two people. Each floor accommodates around 70 workers, typically operating from 8 a.m. to 6 p.m.

The Heating, Ventilation, and Air Conditioning (HVAC) system of the building is divided into eight zones (Figure 2). Mechanical ventilation, heating, and cooling are achieved through a centralized air system, ensuring adequate air exchange in the offices. At the office level, occupants can control the temperature setpoint (+/- 2°C from the central setpoint), window openings, internal shading system (blinds), and artificial lighting.

All areas of the building were investigated through a general satisfaction questionnaire. For the in-depth instrumental and perceptual monitoring of indoor environmental quality parameters, 32 offices within the building were selected (first floor: 1.a, 1.b, 1.c., 1.d, 1.e, 1.f, 1.g; second floor: 2.a, 2.b, 2.c, 2.d, 2.e, 2.f, 2.g, 2.h; third floor: 3.a, 3.b, 3.c, 3.d, 3.e, 3.f, 3.g, 3.h; fourth floor: 4.a, 4.b, 4.c, 4.d, 4.e, 4.f, 4.g, 4.h). The selection criteria aimed to obtain a representative sample and included:

- eight offices per each floor, from the first to the fourth floor. The ground floor was excluded from monitoring due to different occupancy characteristics com-pared to other floors;
- one office for each HVAC zone on each floor;

- availability of occupants in selected offices to respond to questionnaires and participate in monitoring;
- preference for offices with two or more workers to obtain a greater number of subjective responses.

Fig. 1. Corridor and office type.

Fig. 2. Distribution of the HVAC zones.

2.2 Instrumental monitoring of indoor air quality

IAQ monitoring was conducted in the 32 offices of the case study at two levels: long-term and short-term monitoring. Long-term monitoring spanned five weeks during winter 2023 on each room, encompassing measurements of pollutants and thermo-hygrometric parameters. The parameters selected for measurement included Carbon Dioxide (CO_2), Particulate Matter ($PM_{2.5}$, PM_{10}), Total Volatile Organic Compounds (TVOC), Air Temperature (T_a), and Relative Humidity (RH).

In order to monitor all the abovementioned parameters, two different instruments were employed. Air temperature, relative humidity and carbon dioxide were collected by using an in-house developed multi-sensor device called "Environmental Quality bOX" (EQ-OX) [8]. EQ-OX was conceived to be a portable low-cost device that enables to measure multiple IEQ parameters such as hygro-thermal parameters, lighting level, and some IAQ parameters. EQ-OX system gathers multiple readings within 1 min. However, for all analysis conducted in this study, data was previously resampled using 30-min average values. Particulate matter ($PM_{2.5}$, PM_{10}), and TVOC were measured using N2SMART Nuvap sensors. These devices have an integrated mobile connectivity and provide a reading every 30 minutes. Data are stored in real-time on the Nuvap cloud platform.

Sensors were strategically placed based on criteria such as proximity to the breathing zone, central location, avoidance of direct airflow, and sunlight.

To ensure the correctness of the measurements performed, sensors were com-pared against reference instruments prior to the measurement campaign. Air temperature sensors were tested in a climatic chamber in the range of 10 – 35 °C and compared to a high accuracy RTD Pt100 1/10 DIN sensor, whereas the RH sensors were tested in the range of 20 – 80% and compared to E+E EE060 previously calibrated in an accredited calibration laboratory. In both cases, correlation between the sensor and the reference instrument was high (R^2>0.99). The CO_2 sensors were assessed against the Deltaohm HD21ABE17 reference instrument prior on-field measurements. The outcomes revealed satisfactory performance, with a Mean Ab-solute Error (MAE) of 42-43 ppm compared to the reference instrument and an R^2 of 0.91-0.92. The TVOC sensor was factory calibrated while $PM_{2.5}$ and PM_{10} sensors were evaluated against an aerosol spectrometer (GRIMM 11-D), demonstrating acceptable performance: $PM_{2.5}$ MAE ranged from 16 to 18 µg/m³ with an R^2 of 0.91-0.93, and PM_{10} MAE ranged from 14 to 17 µg/m³ with an R^2 of 0.91-0.93.

Short-term monitoring occurred from March 20th to 24th 2023 in four diverse offices on the second floor. This in-depth monitoring aimed to identify specific air pollutants present in the offices. Passive sampling was conducted using Radiello 145 for the capture of Volatile organic compounds (VOC) and Radiello 165 for aldehydes. Then, the sampling tubes were analysed by thermal desorption followed by gas chromatography and mass spectrometry (ATD-GC/MS) in the case of VOC and solvent desorption coupled to high performance liquid chromatography and ultraviolet detection (HPLC-UV) in the case of aldehydes. Since the goal of the monitoring was to determine the potential exposure of the workers to indoor air pollutants, passive samplers were installed during working hours (from 8 a.m. to 6 p.m.).

2.3 Perceived air quality evaluation

To obtain detailed information on PAQ, two questionnaires were developed, namely the "one-off" and the "right here-right now". The questionnaires were developed taking into consideration the most frequent causes of dissatisfaction in offices [9].

The "one-off" satisfaction questionnaire consists of eight sections. The first section aims to collect information on office usage, including working hours, office occupancy, occupancy density, and office location within the building. The second section addresses satisfaction with 14 possible causes of discomfort, rated on a Likert scale from -3 (very dissatisfied) to +3 (very satisfied). These causes include: air quality, thermal comfort, perceived control, dimensions, colour and finishes, furniture, cleanliness, privacy, acoustic comfort, view from windows, natural lighting, artificial lighting, natural ventilation, and mechanical ventilation. The third section investigates the frequency (frequency of occurrence = never, occasionally, often, prefer not to answer) of potential dissatisfaction causes related to indoor environmental quality, such as tiredness, headaches, nausea, itchy/burning/irritated eyes, dry skin, respiratory difficulties, and coughing. The fourth section of the questionnaire assesses productivity during working hours on a Likert scale from -3 (very dissatisfied) to +3 (very satisfied). The fifth section explores perceived control over the environment on a Likert scale from -3 (very dissatisfied) to +3 (very satisfied). In the sixth section, the workers were asked to propose improvement actions regarding the use of the building. The seventh section collects general information, such as gender, age, weight, height, education level, and personal habits (coffee consumption, alcohol, energy drinks, sports activities, sleep quality). The last section of the questionnaire allows participants to provide any additional comments.

The second questionnaire, named "right here-right now," consists of two sections. The first section addresses satisfaction with indoor environmental quality parameters at a specific time, including air quality (acceptance and comfort), thermal environment (satisfaction, comfort, and preference), ventilation (satisfaction and preference), lighting (satisfaction and preference), and acoustic conditions (satisfaction and preference). The questions are presented on 3, 4, and 7-point Likert scales and include multiple-choice answers. The second section of the questionnaire collects general information, such as the participant's ID, the presence of a printer in the office, office occupancy, thermal insulation of clothing, and the participant's mood. The "right here-right now" questionnaire was administered twice a week for five weeks in each office.

The study targeted individuals who are:

- adults;
- working at least partially inside the case study;
- without health conditions that could lead to an alteration of the perception of indoor parameters (e.g., chronic diseases, depressive conditions, hormonal disorders, cardiovascular problems, anemia, metabolism-related issues, motor disabilities, pregnant women, women with evident menopausal symptoms).

3 Results

3.1 Analysis of indoor pollutants

To assess the monitoring results, specific categories were established for each parameter, based on the relevant standards and legislations (see Table 1). CO_2 levels were classified into categories I and II (good), III (acceptable), and IV (bad), following the EN16798-1 standard [10]. Similarly, air temperature limits were determined based on categories I and II (good), III (acceptable), and IV (bad) from the EN16798 standard [10]. For relative humidity, the proposed limits were set as in EN 13779 standard [11] which recommends maintaining relative humidity between 30% and 70% and states that a range from 20% to 80% can still be considered acceptable. PM_{10} categories were based on the European Air Quality Directive. Thresholds for the annual mean were considered good and 1-hour mean average was considered acceptable. As for $PM_{2.5}$, the thresholds selected were those suggested by the United States Environmental Protection Agency (US EPA) and utilized in the RESET standard for continuous air quality monitoring in the built environment. The limits for the annual average were considered good and the 24-hour average was considered acceptable. VOC thresholds were established according to WHO guidelines and have been converted to ppb using the conversion method proposed by Mølhave et al. [12].

Table 1. Thresholds for evaluation of hygrotermal parameters and pollutants.

Parameter	Good	Acceptable	Bad
CO_2 (ppm)	< 1200	1200 - 1750	> 1750
T_a (°C)	20-24	19-20 24-25	< 19 >25
RH (%)	30-70	20-30 70-80	< 20 > 80
$PM_{2.5}$ (μg/m^3)	< 12	12 – 35	> 35
PM_{10} (μg/m^3)	< 40	40 – 50	> 50
TVOCs (ppb)	< 220	220 - 660	> 660

The results obtained for air temperature, relative humidity, and carbon dioxide are displayed in Figure 3. The air temperature generally falls within the green category (20-24°C), with the exception of offices 1.g, 2.e, 4.e, 4.f where the median values are slightly higher (about 25-26°C). For relative humidity, on the first and second floor most offices exhibit low levels, that still fall within the acceptable range (20-30%), except for offices 1.c and 1.g, whose medians are within the green category (30-70%). On the third and fourth floor, the medians are within the green category (30-70%) except for offices 3.b, 3.f, 4.a, and 4.f that showed median values within the acceptable range (20-30%) indicating a slight deviation from the optimal conditions. CO_2 levels consistently remain low, corresponding to the best category in all cases (< 1200 ppm). As regards $PM_{2.5}$ and PM_{10} levels, they typically remain below 10 μg/m^3 for the majority of the time, seldom reaching the yellow zone (< 50 μg/m^3 for PM_{10} and <12 μg/m^3 for $PM_{2.5}$). Concerning VOC levels, they mostly stay within the green category (< 220 ppb).

To assess air quality variations and detect potential system malfunctions, air quality measurements were grouped based on the corresponding HVAC zones (eight in total). All parameters measured in the different HVAC zones were very similar.

Similarly, as with the HVAC zones, the measurement data were aggregated based on the different floors to pinpoint potential emission sources or specific activities that might contribute to pollutant emissions or influence indoor air quality. Across all parameters measured on different floors, substantial similarities were observed, with all the median values falling within the green category, except for relative humidity once again.

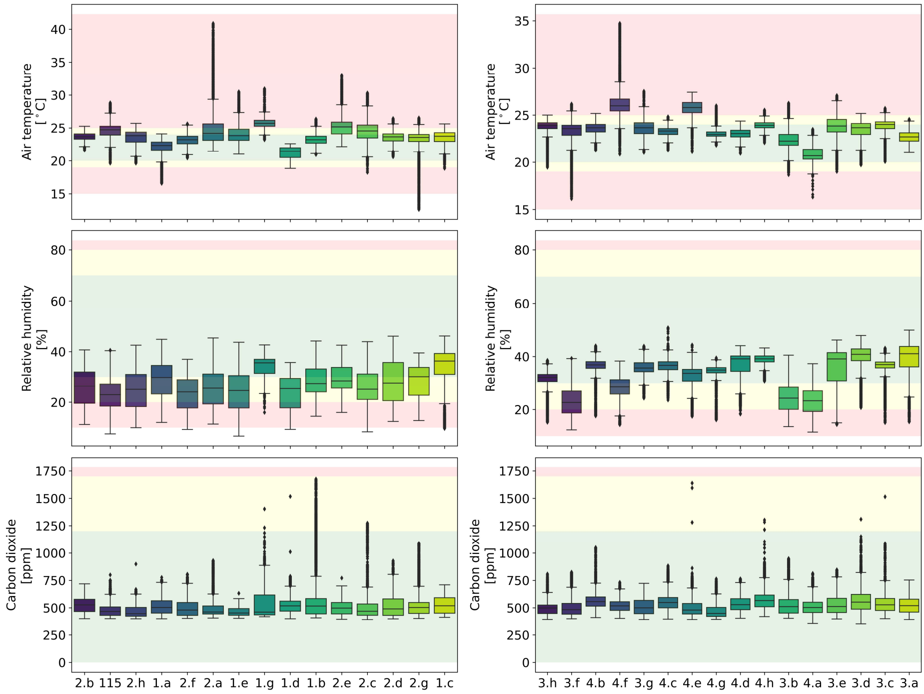

Fig. 3. Air temperature, relative humidity, carbon dioxide on the 1st and 2nd floor and on the 3rd and 4th floor.

Spot measurements were performed during one week in four offices of the second floor (2.b, 2.d, 2.f and 2.h) using a Radiello samplers. Among the 39 compounds analysed, only 21 were present. The average results obtained for 8-h expo-sure (working hours) during a week (Monday to Friday) are presented in Figure 4. The figure illustrates that most VOC concentrations were exceptionally low, measuring below 2 μg/m3. Decane was the compound present at highest concentration in the four rooms. Across the 2.d, 2.f and 2.h rooms, 1,2,4-trimethylbenzene and acrolein were consistently found at concentrations raging between 1 and 2.1 μg/m³. In Room 2.b, a distinctive profile was observed. Apart from acrolein (2 μg/m³,), D-limonene and undecane were present at concentrations of 2.65 μg/m³ and 2 μg/m³, respectively.

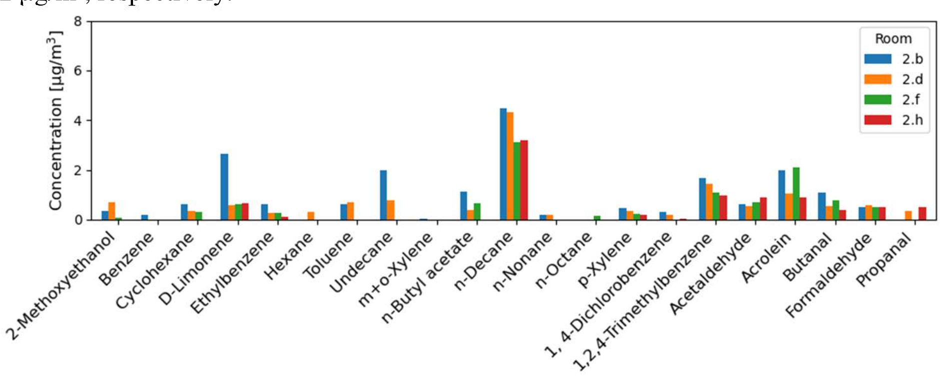

Fig. 4. VOC levels measured in offices of the second floor.

3.2 Analysis of perceived air quality

In the experimental campaign, 180 employees from the case study participated voluntarily. Among these, 67.2% were females, 26.1% were males, and 6.7% preferred not to respond. Regarding age, 38.3% were between 51 and 60 years old, 30% between 41 and 50, 17.2% between 31 and 40, 7.8% between 18 and 30, 1.1% were over 60 years old, and 4.4% preferred not to respond.

Fourteen potential sources of dissatisfaction were examined, using a Likert scale from -3 (very dissatisfied) to +3 (very satisfied). According to the results, the workers showed overall satisfaction or neither satisfaction nor dissatisfaction regarding the Indoor Environmental Quality (IEQ) of their offices, reporting generally neutral or positive average ratings (Figure 5). Among the investigated parameters, mechanical ventilation obtained the lowest average satisfaction score, followed by perceived control, although they did not reach critical levels. Air quality recorded an average score of -0.298, placing it in the neutrality range.

The 14 sources of dissatisfaction were investigated according to the HVAC system's zone and to the floor to highlight any correlations. No significant differences emerged in the dissatisfaction ratings.

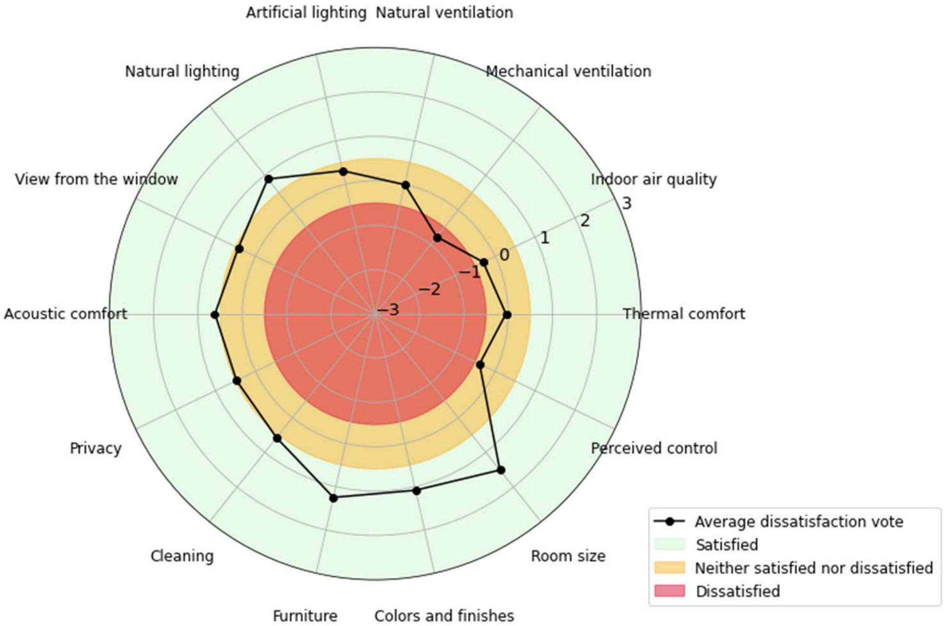

Fig. 5. Causes of dissatisfaction in the offices.

During the investigation into the IAQ in the offices, the 83% of workers de-scribed the air as "dry" and "heavy" (Figure 6). Even when asked to assess the most common general causes of dissatisfaction, dry air proved to be the most prevalent source of dissatisfaction (referred by the 25% of workers).

Through the use of "right here-right now" questionnaires, correlations between IAQ perception and indoor monitored parameters were sought by measuring the Pearson correlation coefficient (r). Regarding IAQ satisfaction, a moderately strong positive correlation is noted with IEQ satisfaction (r=0.55), thermal satisfaction (r=0.48), and ventilation satisfaction (r=0.55). The correlation with indoor pollutants such as VOC, CO_2, and PM is weak (r<0.001). A slightly stronger correlation is observed with thermal parameters such as air temperature (r= -0.055) and relative humidity (r=0.0076).

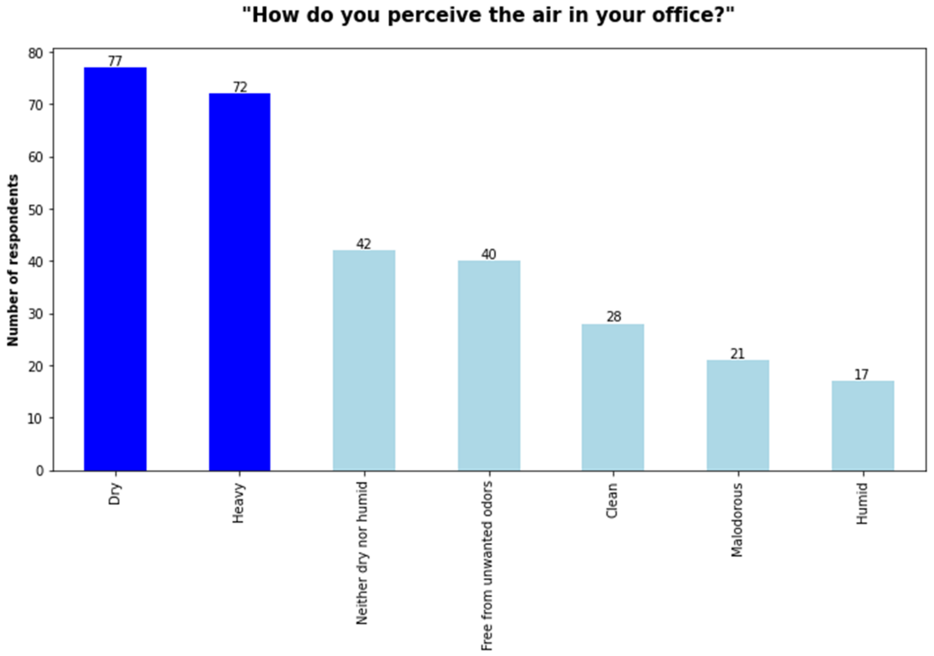

Fig. 6. IAQ perception in offices.

The frequency of the seven nonspecific symptoms was investigated among the 180 respondents (Table 2). From the survey results, it emerged that 29.8% of participants often experienced itchy, burning, or irritated eyes, while 33.7% reported fatigue and dry skin.

Table 2. Frequency of occurrence of symptoms related to SBS as self-reported by the 180 respondents.

	Frequency of occurrence (%)			
Symptoms	**Never**	**Occasionally**	**Often**	**Prefer not to say**
Tiredness	3.3	61.1	33.9	1.7
Headache	22.8	58.3	18.3	0.6
Nausea	69.4	25.6	2.2	2.8
Itchy, burning or irritated eyes	24.4	45.6	30	0
Difficulty breathing	69.4	23.3	5.0	2.2
Dry skin	25.0	37.8	33.9	3.3
Cough during working hours	42.8	51.1	3.9	2.2

4 Discussion

The purpose of the monitoring campaign was to test a POE protocol that assessed three aspects related to IAQ: harmful indoor contaminant thresholds, people's perception, and health aspects. The campaign demonstrated that evaluating these three aspects simultaneously, rather than focusing on each individually, is crucial for characterizing the IAQ. The results from these three types of assessments provided a comprehensive view of the office situation that would not have been possible otherwise. The innovative methodology for evaluating PAQ moves beyond just identifying potential causes of dissatisfaction with IAQ. By adopting a cross-modal approach and studying 14 potential causes of dissatisfaction, the campaign offers a thorough examination of different domains (thermal, visual, acoustic, and IAQ) and their impact on PAQ.

During the winter of 2023, instrumental measurements detected average relative humidity levels below 30% in the 50% of surveyed offices and below 40% in the other 50%. ASHRAE 55 recommends that the optimal relative humidity be in the range of 30-60%, with winter conditions leaning towards the higher limit (40-60%) [13].

Subjective perception questionnaires proved useful in understanding the perceptual aspects of such a result. The fourteen potential sources of dissatisfaction were investigated in line with the multi-domain approach. Overall, people were found to be satisfied or neutral towards the parameters. Most occupants described the air as "heavy" or "dry" (83% of respondents). Through the use of "right here-right now" questionnaires, correlations between IAQ perception and internally monitored parameters were sought. No significant correlations emerged with IAQ parameters like CO_2, TVOCs, PM, and individual VOCs probably because these parameters were below threshold values. Additionally, the limited number of data available for individual VOCs hindered the possibility of establishing potential correlations. However, a slightly stronger correlation was observed with relative humidity and air temperature. The close relationship between thermal parameters and perceived air quality has already been demonstrated in the literature (Fang, 2004).

In line with the low levels of relative humidity detected by instrumental measurements and reported PAQ by individuals, are the Sick Building Syndrome (SBS) symptoms reported by survey participants. These are nonspecific symptoms that can be linked to staying inside a building. A large portion of respondents complained of itchy, burning, or irritated eyes (30% often, 45.6% occasionally) or dry skin (33.9% often, 37.8% occasionally). These discomforts can be attributed to the levels of relative humidity [14]. found in the case study, which are typical of the Autonomous Province of Bolzano.

Perception and SBS questionnaires support the idea that certain indoor parameters can create issues in terms of both comfort and occupants' health, even if they do not exceed threshold values provided by standards. In this field study, this is the case with relative humidity, which, although not exceeding limit values provided by standards, leads to a perception of IAQ as not fully satisfactory (average dissatisfaction score of -0.29) due to being "dry" and "heavy" and the onset of symptoms in workers likely related to being inside the office.

5 Conclusions

The monitoring campaign aimed to comprehensively assess IAQ and its impact on occupant well-being in an office building of the Autonomous Province of Bolzano. The results, drawn from instrumental, perceptual, and health self-assessments, offer valuable insights:

- air quality parameters such as CO2, PM2.5, PM10, TVOCs and aldehydes levels generally fell within acceptable ranges, indicating satisfactory IAQ;
- concerns arose about low humidity in winter in the majority of offices;

- overall, occupants were not completely satisfied regarding IAQ, which was judged to be "heavy" and "dry" by the 83% of respondents;
- correlations between subjective perception and instrumental measurements revealed an association with relative humidity and air temperature;
- participants reported complaints associated with SBS, such as itchy eyes and dry skin, likely linked to low humidity levels;
- the perceptual and health self-assessments indicate that even within acceptable IAQ limits, indoor parameters like low humidity can impact comfort and health;
- for this reason, simultaneously evaluating pollutant levels, occupant perception, and health aspects is vital for a comprehensive understanding of IAQ.

In conclusion, this monitoring campaign underscores the nuanced interplay between instrumental data, occupant perception, and health impacts in assessing IAQ. The findings emphasize the need for a holistic approach to indoor environ-mental quality management, integrating both quantitative measurements and occupants' subjective experiences.

The insights gained from this study are contributing to the development of an effective IAQ assessment protocol for office buildings. The protocol is currently under development and is expected to be operative from Spring 2024, providing a standardized strategy across South Tyrol and neighbouring geographical areas. The case study presented in this paper will be used as a model in several respects, such as physical measurements of IAQ and thermal environment (assessed parameters and KPIs, frequency of monitoring, sensor placement), and questions to ask for multi-domain assessment of PAQ and SBS.

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