Analysis and monitoring of environmental conditions and well-being in remote working environments in northern Italy

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Abstract. This research focuses on monitoring and analysis of indoor environmental quality (IEQ) in buildings where hybrid and remote work is carried out in mountain areas in northern Italy. The aim is to determine how the physical characteristics of remote working environments affect worker satisfaction and well-being, by researching patterns and correlations between the various variables monitored. The objectives described are studied through multi-parameters devices (focus on thermal environments and indoor air quality) and subjective analyses applied to nine case studies in summer and mid-season. The duration of monitoring depends on the time of use of the rooms and is approximately one week for each selected period. The environmental parameters monitored by integrated devices, such as temperature, relative humidity, CO_2, radon, dust, TVOC, pressure, illuminance (lux) and noise level, are then analysed using the EN 16798-1 standard, which defines four categories of IEQ. The subjective analysis through online questionnaires delves deeper into occupants' perceptions of indoor parameters and the ease with which they can modify their environment to increase comfort. The usability of multi-parameter domestic instruments for IEQ parameters is also analysed, in order to determine ease of use, data download and interpretation. The novelty of this work lies in the combined use of low-cost multi-parameter domestic devices and subjective surveys in real remote working environments in mountainous and semi-mountainous areas, and in the critical evaluation of the applicability of EN 16798-1 office categories to home-based workspaces.

Keywords. Indoor Environmental Quality (IEQ), productivity, remote working, IEQ monitoring, subjective analysis

1 Introduction

Scientific literature [1-7] highlights that remote working can help workers balance their work and personal lives while also increase their productivity, but this aspect is still a source of debate and requires further study. In addition to employees working, self-employed workers also carry out activities from their homes, which is why this issue is still of great interest today.

The remote working environments (RWE) have been in-depth examined for its impacts in environmental, sociological, behavioral, organizational and economic aspects. Some studies argue in favor of separate settings for work and non-work activities, by arguing that working from home may lead to conflict in roles, household distractions, feelings of physical isolation and temporal separation, increase in work-related stress, which in turn reduces job satisfaction. On the other hand, there is also a wide range of studies that focus on the positive effects of RWE, such as better work-life balance, flexibility in work settings, environmental-impact reduction, efficient use of organizational resources, better job performance, job satisfaction, and reduction in stress also related to removal of the time spent travelling between home and work.

The collection of scientific articles [1-7] provided offers a comprehensive overview of the current research regarding smart buildings and remote work environments (RWE). These studies collectively emphasize the evolving role of indoor environmental quality and technological integration in enhancing productivity and well-being for individuals working remotely, whether as employees or self-employed professionals. The main research themes emerging from the reviewed literature are summarized in Figure 1 through a keyword map, which highlights the centrality of indoor environmental quality, comfort, productivity and mental health in remote working studies.

The impact of the indoor environment on mental health and productivity is another crucial aspect explored in the literature. Khalid et al. [2] examine the effects of indoor environments on mental health during remote work, particularly in the context of the pandemic. Their findings suggest that the quality of indoor spaces can significantly influence psychological well-being, which in turn affects work performance.

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Manu et al. [1] provide a systematic review of indoor environmental quality in RWE, focusing on parameters such as thermal comfort, air quality, and acoustics. Their work highlights the importance of these factors in maintaining productivity and well-being, emphasizing the need for environments that support these elements to foster effective remote work conditions.

Fig. 1. Keywords for RWE literature review

The development of quality indicators for remote workplaces is addressed by Mura et al. [3], who introduce the Perceived Remote Workplace Environment Quality Indicators (PRWEQIs). This work is pivotal in providing a framework for assessing the spatial and physical comfort of remote working environments, offering valuable insights for designing spaces that enhance employee satisfaction and productivity. Another significant contribution by Mura et al. [1] investigates the relationship between environmental comfort, workplace attachment, and psychological needs in remote working contexts. This study draws on self-determination theory to explore how these factors influence work engagement, highlighting the psychological dimensions of remote work environments. The articles by Salamone et al. [6] offer a survey-based analysis of indoor satisfaction and productivity during lockdowns, emphasizing the critical role of indoor environmental quality in remote work settings. Their research provides empirical evidence on how environmental factors influence user satisfaction and productivity levels. Lastly, studies focusing on the physical environment, such as those by Guo et al. [7], examine how lifestyle, indoor conditions, and work-related factors impact productivity when working from home. These findings are crucial for understanding how different aspects of the residential built environment can be optimized to support remote work.

The reviewed literature highlights the multifaceted nature of RWE, emphasizing the integration of technology, the importance of indoor environmental quality, and the psychological and physical dimensions of remote work. These studies collectively underscore the need for continued research to further understand and optimize the conditions that support effective and healthy remote working practices.

In this study, the indoor environment is evaluated through objective Indoor Environmental Quality (IEQ) indicators and subjective well-being and comfort assessments. Objective IEQ is quantified using multi-parameter monitoring devices measuring air temperature, relative humidity, CO_2 concentration, radon, particulate matter, TVOC, illuminance and noise level. Thermal environment, humidity and CO_2 are classified according to the four categories defined in EN 16798-1, which provide a graded scale of expected comfort and air quality. Well-being and comfort are assessed subjectively through an online questionnaire including Likert-scale questions (0–5) on perceived thermal, air quality, acoustic and lighting comfort, as well as overall satisfaction with the remote working environment. These questions are inspired by existing instruments for IEQ and remote work assessment [1–7]. The combination of objective and subjective data allows us to explore how physical conditions in RWE influence perceived comfort and well-being.

2 Method

A multi-parameters device (thermal, lighting, acoustic environments and indoor air quality) and subjective analyses was applied to nine case studies, described in Table 1.

Table 1. Case study and environmental characteristics

Case Study	Altitude	Building type	Heating emission type	Coo-ling	Room volume (m^3)
1	1.225	flat	radiator	no	31
2	262	flat	radiator	no	104
3	14	flat	floor heating	yes	27
4	5	flat	radiator	no	120
5	1.201	detached house	radiator	no	48
6	262	flat	Air heat pump	yes	89
7	260	detached house	radiator	no	97
8	1330	flat	radiator	no	56
9	1275	detached house	wood stove	no	85

The nine case studies were selected as representative of the mountainous and semi-mountainous (i.e. in the vicinity of the mountains) conditions of northern Italy.

The environmental parameters monitored by integrated devices, such as temperature, relative humidity, CO_2, radon, dust, TVOC, pressure, illuminance (lux), noise level and other parameters were recorded summarized in Table 2.

Five working days representative of the summer period were selected (based on data from the entire measurement period, which varied between two weeks and two months). For these days, the working hours (from 8 a.m. to 4 p.m.) were selected. Temperature, relative humidity and CO_2 concentration were analysed using the EN 16798-1 standard [8], which defines four categories of IEQ (I–IV) based on expected occupant satisfaction. Category I corresponds to a high level of expectation and is recommended for spaces with sensitive occupants; Category II represents a normal level of expectation for new or renovated buildings; Category III corresponds to an acceptable, but less stringent level; and Category IV represents values outside the recommended ranges for normal use, indicating limited or low performance. The commercial dataloggers used in the analysis had comparable characteristics in terms of measurement accuracy, time interval (varying between 1 and 5 minutes) and price.

Table 2. Portable environmental sensors to monitor IEQ in RWE

	Aranet4	AirCare	Netatmo	Airthings Wave Plus
Temperature (°C)	x	x	x	x
Relative Humidity (%)	x	x	x	x
CO_2 (ppm)	x	x	x	x
Atmospheric Pressure	x	x		x
TVOC		x		x
Radon				x
PM		PM2.5, PM10		
Acoustic		Sound pressure level	Noise level	
Illuminance		x		
Electrosmog		x		

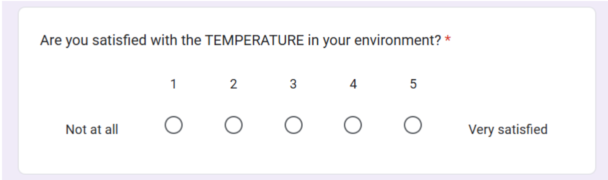

Fig. 2. Example of a subjective question in the online questionnaire

For the air temperature parameter, the analysis was divided between environments with and without cooling: for buildings that were not equipped with cooling systems, the adaptive criterion was applied, i.e. the criterion that considers the moving average of the external temperatures of the previous days.

Instrumental monitoring was accompanied by subjective monitoring. An example of question from the questionnaire relating to thermal comfort is shown in Figure 2.

The aims of the analysis are to:

- evaluate the usability of IEQ monitoring devices
- determine how the physical characteristics of RWE affect worker satisfaction and well-being, by researching patterns and correlations between the various variables monitored.
- identify IEQ improvement strategies in order to increase productivity and reduce discomfort.
- assess whether the values of the comfort categories described in the EN 16798-1 standard for offices are also applicable to smart working environments or whether reference values for residential buildings are more appropriate.

To clarify the calculation of the EN 16798-1 categories, occupancy was assumed during scheduled working hours (08:00–16:00) for the five representative summer working days selected for analysis. The percentage of time in each IEQ category was calculated as the ratio between the number of monitored time steps falling within the threshold limits of that specific category and the total monitored working time. CO_2 concentration categories were assigned according to EN 16798-1, based on concentration levels above outdoor air (Category I: high level of expectation; Category II: normal level; Category III: moderate level; Category IV: values outside recommended ranges). Temperature categories were determined using either fixed or adaptive criteria depending on the presence of cooling systems, while relative humidity was classified according to the recommended ranges defined by the same standard.

3 Results

The extensive IEQ parameter measurement campaign highlighted critical issues relating to air quality, thermal comfort, acoustic aspects, and lighting in some environments. By way of example, the graphs below show some representations of indoor parameter trends.

Figure 3 shows the evolution of CO_2 concentration over two consecutive working days (x-axis: time of day, in hours; y-axis: CO_2 concentration in ppm). Working hours (08:00–16:00) are highlighted in light blue. CO_2 levels increase rapidly during occupancy and reach very high values during the night, indicating insufficient air exchange when windows are closed.

Figure 4 reports indoor air temperature (°C) and relative humidity (%) over the same two-day period (x-axis: time of day). Temperature is relatively stable during working hours, while humidity follows slower variations related to outdoor conditions and occasional ventilation.

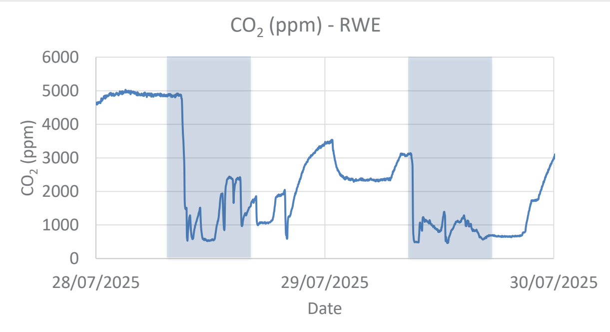

Fig. 3. Example of CO_2 (ppm) monitoring during two days. Working hours are highlighted in light blue.

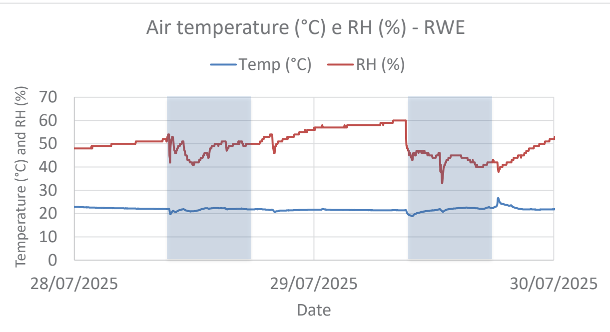

Fig. 4. Example of air temperature (°C) and RH - Relative Humidity (%) monitoring during two days. Working hours are highlighted in light blue.

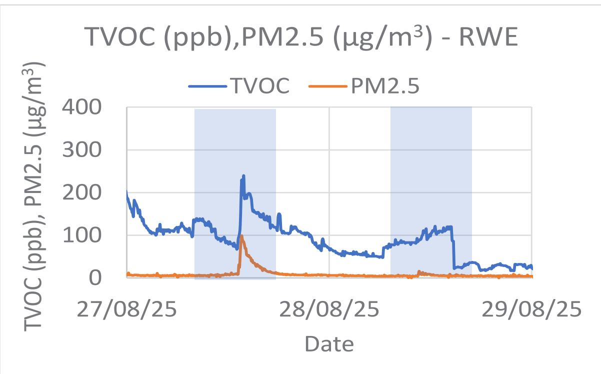

Fig. 5. Example of TVOC (ppb) and PM2.5 (µg/m^3) monitoring during two days. Working hours are highlighted in light blue.

Figure 5 illustrates TVOC (ppb) and PM2.5 (µg/m^3) trends over two days (x-axis: time of day). Peaks coincide with occupant presence and specific activities, showing how user behaviour directly impacts pollutant levels.

It can be appreciated that the concentration of CO_2 can reach very high values, especially during the night time. Air temperature and relative humidity can be more stable, while particulate and TVOC can follow the trend of user presence and user ventilation.

The analysis of the monitoring results, classified according to the four categories of the EN 16798-1 standard, is presented in Tables 3 to 5. The first column identifies the case study number. Each subsequent column (I to IV) reports the percentage of occupancy time during which CO_2 concentrations fell strictly within the thresholds of that specific category. These categories specify different levels of Indoor Environmental Quality (IEQ) based on occupant expectations and building type: Category I represents the highest level of comfort, recommended for sensitive occupants, while requirements become progressively less stringent through Categories II and III. Category IV represents a minimal or limited performance level, indicating values that fall outside the more comfortable ranges.

Table 3. Distribution of occupancy time across Indoor Environmental Quality (IEQ) categories for CO_2 (ppm) concentration, based on EN 16798-1

	I	II	III	IV	Sub.
1	18%	36%	20%	26%	2
2	100%	0%	0%	0%	5
3	95%	2%	3%	1%	5
4	100%	0%	0%	0%	3
5	100%	0%	0%	0%	5
6	100%	0%	0%	0%	5
7	100%	0%	0%	0%	3
8	100%	0%	0%	0%	nd
9	100%	0%	0%	0%	5

Table 4. Distribution of occupancy time across IEQ categories for indoor air temperature (°C) based on EN 16798-1

	I	II	III	IV	Sub.
1	100%	0%	0%	0%	4
2	100%	0%	0%	0%	4
3	100%	0%	0%	0%	5
4	41%	30%	29%	0%	3
5	100%	0%	0%	0%	5
6	0%	0%	0%	100%	4
7	89%	11%	0%	0%	3
8	97%	3%	0%	0%	nd
9	100%	0%	0%	0%	5

Table 5. Distribution of occupancy time across IEQ categories for air relative humidity (%) based on EN 16798-1.

	I	II	III	IV	Sub.
1	54%	46%	0%	0%	4
2	64%	36%	0%	0%	4
3	16%	84%	0%	0%	5
4	0%	100%	0%	0%	3
5	60%	40%	0%	0%	5
6	100%	0%	0%	0%	4
7	100%	0%	0%	0%	3
8	100%	0%	0%	0%	nd
9	17%	83%	0%	0%	5

By providing the discrete percentage for each category, the tables highlight the specific distribution of air quality levels throughout the monitored period rather than a cumulative compliance rate.

The last column with the heading "Sub" describes the subjective vote expressed with the questionnaire. Table 2 shows the categories for indoor CO_2 concentration. The subjective parameter is represented by the responses to the questionnaire, which used a rating scale from 0 to 5, where 0 represented strong dissatisfaction and 5 represented satisfaction.

4 Discussion

Data from nine case studies show how altitude, building type, heating/cooling systems and room volume influence indoor summer temperature, humidity and CO_2, evaluated with EN 16798-1 and occupant feedback. Although the cases differ in altitude and building type, the analysis was limited to comparable summer working days (08:00–16:00), reducing climatic variability effects. Most dwellings fall predominantly in Category I for summer operative temperature, with good to very good subjective comfort, even without mechanical cooling at higher altitudes. A few low-altitude, non-cooled cases show more hours in Categories II–III and only moderate comfort. One RWE with an air-to-air heat pump is technically always in Category IV for temperature, yet users report good comfort, highlighting a gap between normative thresholds and personal preferences. Relative humidity is generally well controlled (Categories I–II only) across all buildings, with satisfactory perceived comfort independent of emission system type. CO_2 behaviour is more sensitive to volume and ventilation: a very small apartment without dedicated ventilation performs poorly (significant time in Categories III–IV and low perceived IAQ). By contrast, almost all other cases, especially larger or detached buildings with better aeration and natural ventilation, remain 100% in Category I with high subjective ratings.

Overall, supporting remote work requires not only thermal comfort but also better air exchange in smaller rooms, via more frequent airing or dedicated systems.

4.1 Usability of IEQ monitoring devices

With reference to the four objectives of this study, the considerations drawn from the surveys (instrumental and subjective) are reported below.

Usability of IEQ monitoring devices

- Multiparameter meters can guide IEQ management in RWEs.
- The parameters measured by most commercially available domestic meters are air temperature, relative humidity and CO_2 concentration.
- These devices must be complemented with dedicated light/noise instruments and targeted questionnaires to fully assess IEQ.

Effect of physical characteristics on satisfaction and well-being

- Small, low-volume rooms with poor ventilation showed the worst CO_2 performance and lowest perceived air quality, while larger or detached homes performed best.
- Altitude and climate favoured good summer temperature and humidity in many cases, often ensuring comfort even without cooling.
- User behaviour and system management can create a mismatch between normative categories and perceived comfort, so building features and habits jointly shape well-being.

IEQ improvement strategies for productivity and discomfort reduction

- The priority is to improve air exchange in smaller rooms, via more frequent airing or dedicated mechanical ventilation, to reduce CO_2 peaks.
- Optimising the use and control of existing heating/cooling systems helps maintain comfort with limited energy consumption.
- Targeted retrofits to make spaces “smart-work-ready” (better envelopes, simple controls, suitable room choice) can reduce fatigue, stress and loss of concentration.

Applicability of EN 16798-1 office categories to smart working

- EN 16798-1 office categories offer a clear, objective basis for comparing IEQ performance in home workspaces.
- However, the study shows that some conditions judged non-optimal by the standard are still perceived as comfortable in residential contexts.
- This suggests office categories should be used as a reference, but possibly recalibrated or combined with residential benchmarks and subjective feedback for smart working.

4.2 Comparison with existing work-from-home IEQ studies

Our findings are broadly consistent with recent reviews and empirical studies on IEQ in RWE. Manu et al. [1] highlights that thermal conditions in home workspaces are often acceptable in mild climates, while air quality and acoustics are more problematic. In our sample, most cases achieved Category I thermal conditions in summer, even without active cooling at higher altitudes, whereas CO_2 levels and perceived air freshness were critical in smaller, poorly ventilated rooms.

Boegheim et al. [5] and Guo et al. [7] report that self-reported productivity and mental well-being are sensitive to perceived air quality and noise. Similarly, in our study, the case with the smallest room volume and worst CO_2 performance also exhibited the lowest perceived air quality and only moderate comfort. Conversely, larger or detached houses with better natural ventilation reported higher satisfaction, in line with [5,7].

Compared with the survey-based works of Mura et al. [3] and Khalid et al. [2], our contribution lies in combining continuous multi-parameter monitoring with subjective assessments in real RWE in mountainous and semi-mountainous areas. This allows us to quantify the gap between normative IEQ indicators and perceived comfort, and to highlight the role of building type, altitude and room volume in shaping IEQ performance.

5 Conclusion

This study provides one of the first empirical datasets on IEQ in real mountainous home-based workspaces combining continuous monitoring and subjective feedback. Multiparameter devices that measured temperature, relative humidity and CO_2 concentration must be complemented with dedicated light/noise instruments and targeted questionnaires to fully assess IEQ. Future work will move from “snapshot” assessments to predictive models to support the design of smart-work-ready homes, extending cases to different building types and urban contexts. A key goal is to link IEQ parameters with productivity, perceived well-being and work-related symptoms, and to explore retrofit strategies that ensure comfort with low energy use and simple controls.

Beyond confirming well-known links between IEQ and perceived comfort, the study provides new evidence on how altitude, building type and room volume interact with occupant behaviors in shaping IEQ in remote working homes, and empirically questions the direct transfer of office-based IEQ categories to residential workspaces.

Another research strand will integrate IEQ with economic, energy and territorial evaluations to identify cost-optimal configurations of office, hybrid and full-remote work. Workers may deliberately lower IEQ (e.g. heating, cooling, lighting, acoustic treatments) for economic reasons, so these “downward adaptations” should be quantified. A cost-optimal “home vs office” model could compare direct and hidden costs of each option, including health, productivity and environmental impacts. This multi-criteria framework would support guidelines for residential design, corporate hybrid-work policies and public incentives, framing IEQ as a central variable in sustainable, equitable remote work models.

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