Indoor air quality monitoring and management in hospitality: an overarching framework

Sara Zanni, Matteo Mura and Mariolina Longo
Department of Management, University of Bologna, Bologna, Italy, and

Gabriella Motta and Davide Caiulo
Department of Research and Development, Planetwatch, SaS, St. Genis-Pouilly, France

Abstract

Purpose – This study aims to provide a comprehensive framework for the study of indoor air quality (IAQ) in hospitality premises. The goal is to identify the drivers of air pollution, both at the exogenous and endogenous level, to generate insights for facility managers.

Design/methodology/approach – The complexity of hospitality premises requires an integrated approach to properly investigate IAQ. The authors develop an overarching framework encompassing a monitoring method, based on real-time sensors, a technological standard and a set of statistical analyses for the assessment of both IAQ performance and drivers, based on correlation analyses, analysis of variance and multivariate regressions.

Findings – The findings suggest that the main drivers of IAQ differ depending on the area monitored: areas in contact with the outdoors or with high ventilation rates, such as halls, are affected by outdoor air quality more than guestrooms or fitness areas, where human activities are the main sources of contamination.

Research limitations/implications – The results suggest that the integration of IAQ indicators into control dashboards would support management decisions, both in defining protocols to support resilience of the sector in a postpandemic world and in directing investments on the premises. This would also address guests' pressing demands for a broader approach to cleanliness and safety and support their satisfaction and intention to return.

Originality/value – To the best of the authors' knowledge, this is the first study developing a comprehensive framework to systematically address IAQ and its drivers, based on a standard and real-time monitoring. The framework has been applied across the longest period of monitoring for a hospitality premise thus far and over an entire hotel facility.

Keywords Indoor air quality management, Hospitality, Hotel management, Indoor air contaminants

Paper type Research paper

1. Introduction

The pandemic taught us a hard lesson about the importance of data for making strategic decisions, implementing emergency measures and planning for recovery – as well as the

difficulty of defining a purpose-driven framework for data collection and analysis. These issues deeply and equally affected all aspects of our lives and economic sectors.

The hospitality sector, in particular, has experienced an unprecedented discontinuity in its performance during the pandemic. Overall, reports estimate that severe acute respiratory syndrome coronavirus 2 has caused a nearly 80% loss in tourism revenues (UNWTO, 2020). Confirming this point, preliminary field studies have evaluated the current crisis as seven times more economically impactful than the one triggered by 9/11 in the USA (Sigala, 2020). Previous epidemics already generated an impact on the sector, but the effects were limited to the areas where the outbreaks emerged (e.g. Hong Kong for severe acute respiratory syndrome coronavirus 1, where hotels' registered occupation rates fell to 20% and, in some cases, lower than 10% during the peak of the epidemic). Like educational, recreational and professional facilities, hospitality venues have applied strict protocols to regulating environmental disinfection and social distancing (Theuring et al., 2021). Considering the concrete possibility of crises after COVID-19, the hospitality sector needs to develop new approaches and processes to support both crisis management and resilience (Chan et al., 2021; Lai and Wong, 2020; Pillai et al., 2021; Wut et al., 2021). In this sense, the environmental quality of the hospitality experience will become a strategic asset for the postpandemic recovery. Thus, a "new normal" must be outlined for hospitality, with enhanced safety protocols that account for a wider set of practices and, consequently, performance indicators. Research can support the hospitality sector in developing advanced management systems (Jiang and Wen, 2020).

With our work, we aim to contribute to this effort by proposing an overarching framework for the study of indoor air quality (IAQ) on hospitality premises. The COVID-19 crisis has shined a spotlight on this topic, given the tragic impact of poor air quality on rising infections and deaths (Bourdrel et al., 2021; Meo et al., 2021; Pozzer et al., 2020; Setti et al., 2020). Even in non-pandemic conditions, air pollution is regarded as responsible for the loss of life expectancy from long-term exposure at a level comparable with that of tobacco smoking and exceeding that of infectious diseases (Cohen et al., 2017; Lelieveld et al., 2020). Considering that we typically spend between 85% and 90% of our time indoors (Klepeis et al., 2001), the IAQ results are particularly relevant for human health. For these reasons, we developed an overarching framework for the systematic study of IAQ and its drivers, based on the implementation of an innovative sensor network in different areas of the premises, alongside the application of a comprehensive set of statistical analyses to inform the management about possible issues and applicable measures. Then, we applied our framework to a hospitality premise in Italy, collecting data on different environmental and air pollution parameters, with high frequency (i.e. 5-min intervals) across more than six months. We also studied the drivers of IAQ: both endogenous (i.e. human activities, such as standard cleaning, disinfection, cooking and room occupation, as well as air treatment and ventilation) and exogenous (i.e. outdoor conditions, such as the changing seasons, and air pollution). Our findings offer support for the hospitality sector in terms of both recovering from the present crisis and proactively preparing for the future. We provide the groundwork for implementing advanced management systems (Jiang and Wen, 2020) that can optimize operations while promoting health and safety for both guests and staff.

The remainder of the paper is structured as follows: Section 2 reports the definition of the framework for investigating IAQ on hospitality premises, based on the extant literature. Section 3 presents how the framework has been applied to a real case, with details about the site, the monitoring modes and the applied analysis. Section 4 reports the main findings, with respect to the overall performance and study of IAQ drivers. In Section 5, we discuss the main findings in light of current knowledge and draw the main implications for the hospitality sector. Section 6 concludes the paper, marking the present study's novel elements, inherent limitations and pathways for future research.

2. Background and framework definition

The hospitality literature has investigated the management of environmental aspects from different scopes, such as sustainability in general, cost management and customers' behavior and orientation (Chan and Hsu, 2016). Among the different aspects addressed, air quality has only gained attention in recent years as the topic has captured more general awareness (Yang *et al.*, 2022), both at hotel managers' (Chan *et al.*, 2015) and consumers' level.

Recent studies demonstrate that IAQ enters customers' perception under different perspectives. First it has been identified as a key factor of sleep quality (Mao *et al.*, 2018; Zhou *et al.*, 2014) and travel-related insomnia (Xiong *et al.*, 2020). Second, IAQ and *indoor environment quality–related issues strongly impact online reviews of hospitality premises* (Villeneuve and O'Brien, 2020). *Finally, it contributes to the perception of cleanliness* of the premises (Magnini and Zehrer, 2021). This element results particularly strategic during the pandemic crisis: being able to substantiate the safety of cleaning protocols and the perception of cleanliness may represent a strategic asset in a postpandemic world (Chang *et al.*, 2021; Jeong *et al.*, 2022). The monitoring, analysis and display of environmental parameters, and IAQ in particular, respond to the call for instruments to this purpose and increase the awareness toward the green aspects of hospitality for guests and personnel (Raza and Khan, 2022). There is a growing interest toward practices combining sustainability and innovation and their ability to enrich the assets available for the hospitality sector. Within the eco-innovation literature, IAQ has been identified as an element of eco-efficient strategy for hotel premises, but still analyzed by very few studies (Sharma *et al.*, 2020). Furthermore, the field still lacks an overall framework, as studies currently available appear limited whether in terms of area coverage, timespan of the investigation or parameters monitored. To overcome this fragmentation in terms of scope and methodologies, we propose an overarching framework that supports the implementation of smart monitoring networks and data analysis and thereby offers insights for IAQ management on hospitality premises (Figure 1).

First, we propose that the same monitoring and analytical framework should be applied to the different areas of the hospitality premise. This would provide both a general
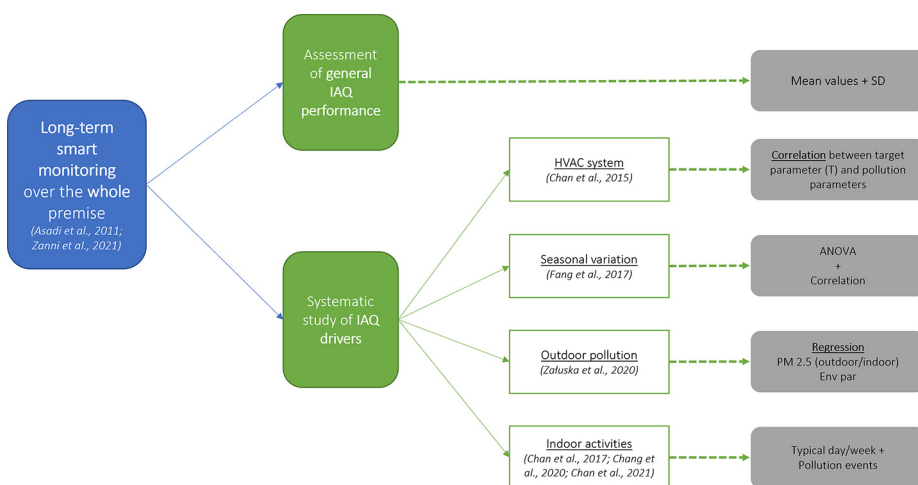

Figure 1.
Framework proposed
for the study of IAQ
on hospitality
premises

assessment of IAQ performance at the building level and specific insights for distinct areas (Asadi *et al.*, 2011). So far, IAQ has mainly been investigated within private rooms (Chan *et al.*, 2009, 2015, 2017; Chang *et al.*, 2020; He *et al.*, 2016) due to a focus on guests. With our framework, we aim to evaluate both guests and staff exposure to provide managers with more holistic information. We also note that a proper IAQ characterization requires a long period of monitoring to capture the complex dynamics of IAQ and its interactions with contour conditions that evolve over time. Moreover, this approach is able to overcome singularities generated by specific events. The majority of studies have limited their investigations to spot sampling, i.e. 1 to 3 h (Chan *et al.*, 2017; He *et al.*, 2016; Lee *et al.*, 2001; Wallace and Ott, 2011), or short periods, i.e. one night to a few days (Chan *et al.*, 2020, 2009, 2015). In most cases, targeted experiments are performed to reproduce specific activities (e.g. cleaning or physical activity) than trace their impact on IAQ. There are very few examples of investigations that cover longer periods and regular working conditions (Chang *et al.*, 2021; Zanni *et al.*, 2021).

Following the literature, and the green building certification schemes for corporate and hospitality buildings (Wei *et al.*, 2020), we propose a comprehensive set of parameters to investigate carbon dioxide (CO_2 – part per million, ppm), total volatile organic compounds (VOCs – ppb) and particulate matter (PM2.5 – $\mu g/m^3$). PM results are relevant for both short- and long-term effects on human health: It is recognized as a carcinogen (WHO/Europe, 2010) and an antecedent of respiratory (Paterson *et al.*, 2021) and cardiovascular (Cohen *et al.*, 2017) diseases, as well as positively correlated with both increased mortality and morbidity related to COVID-19 (Marquès and Domingo, 2022). VOCs have also been mapped in several studies (Asadi *et al.*, 2011; Chan *et al.*, 2009, 2015; He *et al.*, 2016; Lee *et al.*, 2001; Zanni *et al.*, 2021) due to their abundance in indoor environments (Gao *et al.*, 2021; He *et al.*, 2016) and the associated exposure risk (Paterson *et al.*, 2021). In addition, we considered a few environmental parameters that are typically monitored in light of their relevance for facility management: temperature (T, measured as °C), relative humidity (RH, measured as %) and ventilation rate. T and RH can support, on the one hand, the assessment of efficient management of heating, ventilation and air conditioning (HVAC) system. On the other hand, T and RH readings may enhance the interpretation of IAQ parameters, based on optimal detection intervals of the sensors applied (Feinberg *et al.*, 2018; Liu *et al.*, 2019; Liu *et al.*, 2020), thus accounting also for local climatic conditions. As the measurement of ventilation rate is not always accessible, CO_2 has become a proxy for the effectiveness of ventilation in an indoor environment in relationship to its occupation, thus making it primarily relevant for the management of indoor environments during the pandemic.

Second, we state that the IAQ performance assessment requires a standard reference for IAQ, in accordance with Chang *et al.* (2020), defined at the international level, considering the global scale of the hospitality market, which would be able to boost the perception of IAQ and convey the value intrinsic into its management, both toward organization and consumers (Sharma *et al.*, 2020). This standard should provide threshold concentration levels for the main air contaminants, in accordance with international guidelines for indoor environments (e.g. United States environmental protection agency sets a short-term standard for PM 2.5 over a 24-h mean value of 35 $\mu g/m^3$). It should also cover the monitoring methodology and devices and thereby support the comparability of results for the sake of creating a benchmark. At present, a remarkable opportunity is offered by RESET ("Regenerative, ecological, social and economic targets" from GIGA, Shanghai), an internationally recognized commercial standard that covers the collection, transmission and storage protocols of sensor data. This set of criteria provides completeness and reliability to

the generated data set, as well as delineates the threshold values for indoor air pollutants, in terms of level of acceptability and high performance (https://www.reset.build/standard/air). Even though RESET is not specifically designed for the hospitality sector, it can be applied to both the IAQ of commercial buildings and to centralized ventilation systems.

The preliminary IAQ investigation can be accomplished by evaluating the mean values and standard deviations (SDs) of each monitored parameter, in comparison with the defined standard. The analysis of mean values verifies the general compliance with the standard, while the analysis of SD provides a measure of how much the population of collected data is sparse during the period. Considering that hospitality premises are often supplied with central ventilation systems, the variations of environmental and IAQ parameters are expected to be minimal (i.e. low values of SD). On the contrary, in the presence of high SDs, it is reasonable to conclude that perturbing factors are present in the areas, which merits an investigation into the drivers of air pollution.

Third, we define a systematic approach for the study of IAQ drivers, addressing factors that are both endogenous (such as ventilation and human activities) and exogenous (such as seasonal conditions and outdoor air pollution) by means of specific statistical analyses. Most studies in the field have focused on the activities in guestrooms, like showering, walking (Chang *et al.*, 2020) or smoking, when permitted (Chan *et al.*, 2017). Regarding restaurants and dining areas, scholars have examined different cooking styles (Lee *et al.*, 2001), such as open-flames and grills (Wallace and Ott, 2011) or restaurant layouts (Chang *et al.*, 2021; Wallace and Ott, 2011).

In this framework, we propose a set of analyses to assess a standard series of IAQ drivers. Considering that most hospitality premises feature an air ventilation system, we assess its ability to influence IAQ to verify the proper functioning, identify elements for improvement and support maintenance efforts. In particular, when an air treatment system is in place, we argue that management should assess its performance on a regular basis (Chan *et al.*, 2015). As the automatic tuning of the HVAC system is accomplished based on a target parameter (typically temperature or a combination of temperature and relative humidity), it is reasonable to verify the correlation between the target parameter and the monitored IAQ parameters (i.e. CO_2, PM 2.5 and VOC). The positive and significant correlation would suggest that the HVAC system is able to influence IAQ and must be regarded as a driver, thus signaling that the system should be tuned to optimize the IAQ management. On the contrary, low correlation factors would indicate that other covariates may be driving variations in the environmental and IAQ parameters, which would require further investigation on the IAQ drivers. As we will detail later, our results affirmed both of these expectations.

We focus, then, on seasonal variations and how they may affect IAQ in relation to different working conditions of HVAC, as well as the changing of contour conditions, such as sun exposure and the related mechanisms of secondary pollutant formation (Dèdèlè and Miškinytė, 2016; WHO/Europe, 2010). These factors can be investigated by creating subsets of environmental and IAQ data and then examining the variance among groups, for example, by applying an analysis of variance (ANOVA) with season as the grouping variable (Fang *et al.*, 2017). Because seasonal variation can combine with the effects of the air ventilation system, the correlations among parameters should be evaluated a second time. In other words, one should create subsets of data based on the season to account for seasonal adjustments of the HVAC system (e.g. switching the heating/conditioning on/off).

Because we consider outdoor air pollution to be a possible driver for IAQ, it is necessary to first identify possible associations and trends between indoor and outdoor pollution levels, namely, by means of correlation analyses (El Kenawy *et al.*, 2021; Liu, Zhou, *et al.*,

2020; Zhong *et al.*, 2019). Second, in areas where this association can be proven, a causality relationship must be identified by means of multiple linear regression (MLR). MLR is applied to test the relative impact of both outdoor pollutants and indoor environmental parameters (i.e. temperature and humidity), as possible covariates, on IAQ (Załuska and Gładyszewska-Fiedoruk, 2020).

Finally, in considering human activities, we analyze patterns of air pollution by evaluating the typical day (based on hourly mean concentration values) and the typical week (based on the combination of hourly/daily mean concentration values). This offers a global view of the pollutant behavior over time. On the one hand, this offers information about recurrent patterns that are possibly related to systemic aspects (e.g. HVAC overload) or routines (e.g. cleaning), as indicated by mean behavior. On the other hand, it indicates the significance of exceptional events (e.g. specific activities), as indicated by SD.

We complete the study with a focus on pollution events, which are identified based on concentration values (i.e. hourly means, exceeding the RESET standards for CO_2, PM 2.5 and VOC) and mapped across the different areas monitored, in terms of number of occurrences and percentage incidence. Areas reporting a relevant occurrence of pollution events need to be further investigated in light of other drivers and specific activities that emerge during the assessment. The study of pollution events occurring in guestrooms during the check-in time appears particularly relevant for the management, given the pandemic's major risk of possible cross-contaminations between subsequent occupants of the same room. Consequently, developing processes that can identify issues and test the possible solutions is a strategic asset for resilient hospitality premises.

A holistic study of IAQ should reflect the true scale and typical working conditions of a venue. That said, targeted experiments may be set up to countercheck the analytical results, especially when studying human activities as a driver of IAQ, but this falls outside the scope of the present study.

3. Field test methodology
The proposed framework was developed based on the monitoring of environmental and IAQ parameters by means of a network of low-cost, commercial-grade monitoring stations.

3.1 Data collection
The different parameters are detected by a dedicated sensor, as in Zanni *et al.* (2021). Each monitoring station is connected through an integrated communication module, including Bluetooth 4.1., Wi-Fi connection 802.11 b/g/n @ 2.4 GHz, cellular (4 G LTE) gateway and Bracket bundle, LoRa gateway, Ethernet gateway and Bracket bundle. The size of the monitoring station is limited to $10 \times 10 \times 3.5$ cm. The monitoring stations comply with some relevant green building certifications, such as WELL, LEED, Fitwel, LBC and RESET. The monitoring network has been implemented and data collected and shared by PlanetWatch SaS.

The experiment was set up by following Zanni *et al.* (2021), with the installation of a whole RESET-compliant monitoring network over a single hospitality premise. The covered areas were both for public use (i.e. the reception area, including both the hall and lobby; the kitchen and the restaurant; and recreational area, including the fitness center) and private use (i.e. 24 guestrooms). This represented the first case in Europe, and the second in the world, of a hotel premise being monitored based on RESET air quality standards. Each parameter was sampled every 5 min for a period of 185 days, i.e. from mid-February to the end of August 2021. This allowed us to achieve what is, to the best of our knowledge, the longest IAQ indoor monitoring on a hospitality premise and the richest data set of its kind.

The hospitality premise features 144 rooms spread across four floors. The building is equipped with a centralized HVAC system that draws fresh air from the outside of the building, treats the input air and distributes it uniformly to all the different areas, except in the kitchen, where the ventilation is enhanced by manually tuning the extractor hood. The air treatment system is based on photocatalytic oxidation (PCO) technology, which exploits a complex series of chemical-physical reactions, including the advection of the contaminated air flow over a photocatalyst's surface; the pollutants are then diffused into the micropores of the reactor, adsorbed on the interior surface, undergo photon-driven reaction, and finally, the by-products are desorbed alongside CO_2 and vapor (Li and Ma, 2021). The high energy provided by the photons, combined with the additional boost of the catalyst, makes this process one of the more effective in removing indoor air pollutants. Each air outlet is equipped with a PCO unit, supplying treated air to the area. The hotel management was provided with a dedicated dashboard that offered direct and real-time access to the results of the monitoring activity.

3.2 Data analysis
The collected data were analyzed based on the proposed framework. We calculated correlation by processing the data set with OpenAir R package, which is currently recognized as a solid tool for air quality data analysis. The tool has been developed using R-Forge (Theußl and Zeileis, 2009) at King's College in London, by the organization responsible for the city's air monitoring network (Carslaw and Ropkins, 2012). Even though the tool is typically applied to outdoor air quality data, it is adaptable to different set-ups thanks to a library of possible analyses, developed in R programming language, which are free and open source.

The ventilation system we examined did not allow us to fractionate or limit its effect and thereby cover the entire building equally. Consequently, we studied the effect of ventilation with the application of Pearson's correlation among environmental and IAQ parameters. In this way, we could study the possible association among them, as a high correlation factor among parameters would suggest that a common driver is responsible for their behavior. Considering that the temperature regulation is the sole driver for HVAC tuning, it would be reasonable to identify it as responsible for some, if not all, of the parameters.

To study seasonal conditions, we considered the Central Europe calendar: "Winter" for data collected in February; "Spring" for data collected during March, April and May; and "Summer" for data collected during June, July and August (Hänsel *et al.*, 2019). Because the significance of the ANOVA results may simply reflect the abundance of data (Gigerenzer, 2004; Ziliak and McCloskey, 2004), we need to also evaluate the differences in the mean values in the different subperiods and consider their relevance compared to the absolute values.

Regarding the outdoor air pollution, we selected PM 2.5 as a proxy for a general urban pollution. We requested data about the nearest public monitoring station from Agenzia Regionale Per l'Ambiente Piemonte (ARPA Piemonte – Stazione ARPA Lingotto, available at https://aria.ambiente.piemonte.it/#/qualita-aria/dati), i.e. the local environmental authority. As data is only made publicly available in terms of daily means, we elaborated indoor PM 2.5 data in the same form and proceeded with the analyses. For the MLR, the overall fit of the model was tested by F-test, i.e. variance explained, and the relative contribution of each of the independent variables. The MLR model is expressed as follows:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \varepsilon$$

where y is the dependent variable (i.e. PM 2.5 concentration indoor); x_i captures the independent variables (i.e. x_1, x_2 and x_3 are the average PM 2.5 concentrations for outdoor, temperature and indoor humidity, respectively).

Regarding pollution events, we focused on areas of the hotel with higher concentration variability and a lower detectable impact of outdoor air pollution.

To build a reference for identifying pollution events, we conducted a solicitation test in two guestrooms and the fitness center. We simulated the typically prescribed COVID-19 cleaning operation by having two people in the room using wet disinfectant wipes on surfaces. We then checked the concentration values registered by VOC and PM 2.5. Next, we compared our results with other spontaneous events recorded in the same areas and evaluated the mean recovery time, after the pollution event, by studying the shape and slope of the curve. Considering the pollution events registered in the guestrooms, we checked the occurrences of concentration values that were not compliant with RESET standards for CO_2, PM 2.5 and VOC at the check-in time, for each guestroom, to verify whether the standard is met at rest condition and to what extent the pollution events are related to pure human activities.

4. Results

Below, we briefly report the results obtained from the monitoring activity and the performed tests. The complete analytical results are available in the Appendix and from the authors, upon request. We collected data for more than six months, generating over 50,000 observations for each area monitored. This allowed us to first verify the general IAQ performance on the premise, differentiated by area. Based on the mean values registered, we observed differences in each area across all the parameters, both environmental, i.e. T and RH and IAQ, i.e. CO_2, PM 2.5 and VOCs (see Table A1). These differences were more marked for PM 2.5 and VOCs, from 60% to 90%, while T, RH and CO_2 presented more limited differences, i.e. from 10% to 20%. Moreover, considering SD, we saw that T and CO_2 presented values correspondent to about 10% of the mean values, while RH reported about 30% and PM 2.5 and VOCs presented SD values about 150% and 220% of the mean values. We then used correlation analysis to verify whether there is an association among the monitored parameters and assessed the impact of the HVAC system, using the correlation with T as a proxy. The environmental and IAQ parameters were not correlated with one another, at least when considering the whole period of monitoring. When splitting the time series into seasons, however, we found some degree of correlation among temperature, humidity and CO_2, during winter and summer when the heating and cooling systems work to control the target parameter (i.e. T). These results affirm that the air ventilation system is able to control environmental parameters and CO_2, with a lower performance on RH, even though, at a general level, it is not able to prevent high fluctuations in air pollutants, such as PM 2.5 and VOCs. Considering that T is the target parameter for the HVAC system and CO_2 is directly influenced by the ventilation of exhaust air and fresh air feed, it is reasonable to assess that the HVAC system generally performs properly, even though IAQ presents evident instability (e.g. into guestrooms).

To elaborate further on seasonal variation, we performed an ANOVA and confirmed that there are significant differences in environmental and IAQ parameters based on seasons. Considering the high number of observations within the sample, we proceeded with the analysis of mean values across the seasons and areas to capture the power of such variations (see Table A2). We observed that T is maintained almost constantly across the seasons, except in the fitness center, where there is a seasonal increase; RH increased during the summer in all the areas; and PM 2.5, in general, registered a decrease with the changing seasons, particularly in the transition from winter to spring. For VOCs, the changing

seasons led to an uneven evolution, with decreases in some environments (i.e. hall, lobby, kitchen and restaurant) and increases in others (i.e. fitness center and guestrooms).

To verify the influence of outdoor air pollution over IAQ, we used Pearson's correlation to compare the PM 2.5 concentrations in the hotel with the correspondent daily mean values published by ARPA Piemonte for the monitoring station in Torino Lingotto. The results suggest that there is a positive correlation between outdoor and indoor PM 2.5 for almost all areas, except for guestrooms. This implies that we recognize the same decreasing trend in indoor concentrations that we verify in outdoor. The decrease in PM 2.5 with the proceeding seasons, from winter to summer, is a typical feature of the geographical context. As the test site is located in the highly urbanized area of Turin, wintertime registers remarkable levels for air pollution, especially related to PM (Bo *et al.*, 2020), due to a combination of factors. On the one hand, the typical PM 2.5 sources in urban areas, i.e. households heating systems and road traffic, are more active in winter. On the other hand, in the area of the Po valley, surrounded by the Alps, cold months corresponds to a lower atmospheric mixed layer, while warmer seasons trigger winds phenomena able to dilute the pollutants and limit their accumulation, resulting in lower concentrations. It is worth noticing that similar results are obtained also in completely different climates (Sahu and Gurjar, 2020), where the dilution effect of air pollutants is generated by rainfall washout.

Next, we extended the analysis to identify a causal effect of PM 2.5 registered outdoor ($PM2.5_o$) over PM 2.5 values indoor ($PM2.5_i$), using T and RH detected indoor as covariates, into the same environment. $PM2.5_o$ and T were statistically significant predictors of $PM2.5_i$ for most of the areas, while RH's effect was limited to only some (e.g. the hall and lobby). The high R^2 suggests a good fit of the model for the data. Focusing on the guestrooms, the poor correlation was corroborated by multiple regression results, as only $PM 2.5_o$ displayed a sufficient level of significance to be included in the model. Nevertheless, the model presents an R^2 so small that its explanatory power is irrelevant ($R^2 = 0.04$ – see Table A3). Therefore, it is reasonable to conclude that the levels of $PM 2.5_i$ detected in the guestrooms are independent from the outdoor concentrations, and therefore, they are exclusively related to the specific activities performed in the indoor environment.

Finally, considering the marked differences of IAQ values in the areas monitored, we evaluated the impact of specific activities performed in each area by evaluating the patterns of contamination. We examined the typical day and week of each area and drilled down to evaluate the events of contamination in the guestrooms, where the IAQ proved to be the most unstable and the outdoor air pollution displayed a limited impact on the IAQ.

The trends of the IAQ differed sensibly along the typical day and week, depending on the area evaluated, the season and the contaminant of interest. We could identify specific patterns in each area; based on the timing of the peaks and the general distribution of the data across time, it is possible to link the recurrent pollution events with the routine operations performed on the premises. In particular, public spaces appeared to be affected by operations like cleaning and cooking, while private areas presented a more varied distribution of IAQ. First, considering cleaning operations, they clearly affected the IAQ in the fitness center, kitchen and restaurant. On the one hand, the fitness center presented no recurrent peak patterns for PM 2.5 but did present a clear pattern for VOC in two particular intervals: early in the morning, just after 6 o'clock in winter and spring and with a higher peak value and wider area in summertime; and late in the afternoon, around 7:00 p.m. (Figure 2). These are the two moments of the day when guests (and especially business guests) are most likely to frequent the fitness center. Due to COVID-19-related measures, each fitness machine must be sanitized between two subsequent users; therefore, disinfectants are applied, and their impact is affirmed by the presence of VOCs. We confirmed this association by reproducing the peaks of VOCs, in terms of both intensity
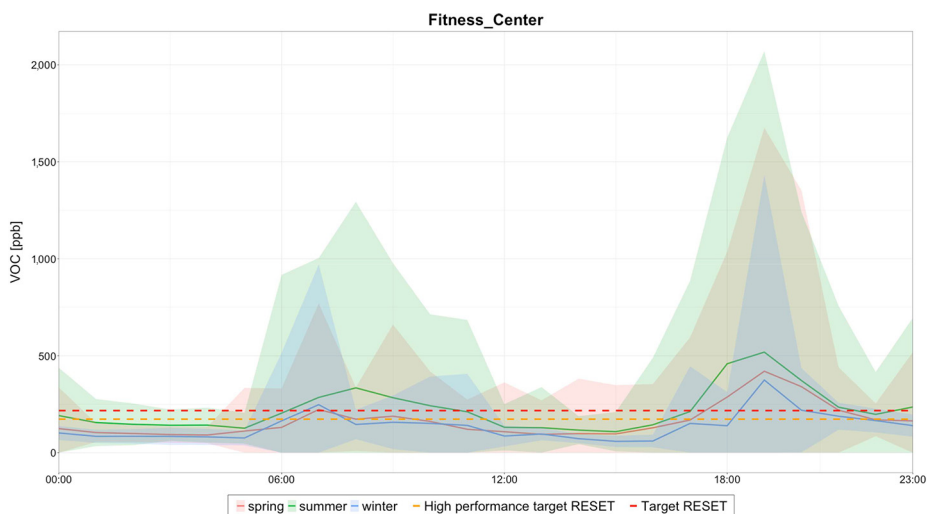
Figure 2.
Typical day pattern
in the fitness center
for VOC, seasonal
differentiation

and duration, with the application of cleaning wipes to fitness machines as prescribed by the protocols. Unfortunately, the concurrence of peaks in contamination and the activities performed into this specific environment may represent a cause of concern, as people in exercise are the most exposed to adverse effects of air pollutants, compared to people at rest, due to higher respiration rate and physical stress (Carlisle and Sharp, 2001; Xie *et al.*, 2021). In the kitchen and restaurant, meanwhile, the VOCs' peaks appeared to be differently distributed: particularly in the late night and early morning, when those areas are typically subject to cleaning.

Second, considering the cooking operations of the kitchen and restaurant, we saw recurrent peaks on PM 2.5 overlapping with cooking and service time, respectively. In the kitchen, we detected peaks between 7:30 a.m. and 9:30 a.m. (i.e. during the breakfast hour), around 11:00 a.m. (i.e. just before lunchtime) and between 5:30 and 10:30 p.m. (i.e. from the preparation of the dinner line to the end of the service). This supports findings from previous literature in the field (Chang *et al.*, 2021; Lee *et al.*, 2001) that link the PM pollution to cooking activities. The kitchen did not report excess peaks in PM 2.5, compared to the RESET standards, with just a few exceptions for VOC, and lower levels of contamination compared to previous empirical studies. This is most probably related to the fact that:

- the hotel restaurant offers a varied menu, without a marked prevalence toward specific cooking styles, similar to Lee *et al.* (2001); and
- a hood ventilation system is activated over the service periods to remove the fumes (Chang *et al.*, 2021), limiting personnel exposure and diffusion into the dining areas.

In the restaurant, we saw two recurrent peaks occurring between 10:00 a.m. and 12:00 p.m. (i.e. between breakfast and lunch time) and a secondary one between 8:00 and 10:00 p.m. (i.e. at dinnertime).

Third, private areas (i.e. guestrooms) exhibited peculiar trends on the whole set of IAQ parameters, with extreme variations within the data as evidenced by the high SDs. Peaks of PM 2.5 concentration that registered in the wintertime, late in the morning and in the early evening, progressively disappeared through typical days in the spring and summer

(Figure 3). In particular, guestrooms are the areas where IAQ presents more events that exceed the RESET standards (i.e. pollution events). Thus, we investigated the relationship between pollution events and room occupancy. The obtained results indicate that peaks in VOC occur in the morning and evening hours and are highly related with room occupancy (see Table A4 for details). In the first case, activities performed by guests are the most likely causes of the peak concentrations; in the second, cleaning routines can also contribute to the air pollution. Almost all the rooms, with the exceptions of Room D and Room R, present a correspondence between peaks and occupancy above 85%, and 50% of the rooms actually present a correspondence of 95% or above. The two rooms presenting anomalous behavior have been marked as areas of concerns that require further investigation – in terms of, for example, inspecting ventilation ducts. We estimated the recovery time of the IAQ control system after the pollution events between 70 and 80 min for VOCs and about 19 min for PM 2.5, thus uncovering the ideal time between the cleaning operations and new occupation of the guestrooms to ensure a proper IAQ for the guests. With the same scope, we also detailed the distribution of pollution events over time to verify whether the IAQ at the typical check-in time meets the RESET standards. We found that PM 2.5 concentrations only rarely exceeded the standard (0.6% occurrences), and this was only slightly higher for VOCs (4.5% occurrences) (see Figure A1 for distribution).

Finally, considering the CO_2 concentrations, room occupation caused an evident accumulation of this contaminant during the evening. The typical week indicates a seasonal behavior: in both winter and spring, the working week presents the higher concentration values, while in the summertime, the weekday and weekend evenings showed comparable values (Figure 4). This suggests that the COVID-19-related restrictions had an impact on the premise, because they were limited to business travelers until the summertime, when tourists were allowed to travel once again. This trend was confirmed by PM 2.5 concentration in the hall, where the summertime displayed concentrations similar to the typical week, while there were higher concentrations in the springtime during the central days of the week. This suggests that business travelers were more prevalent during those days.
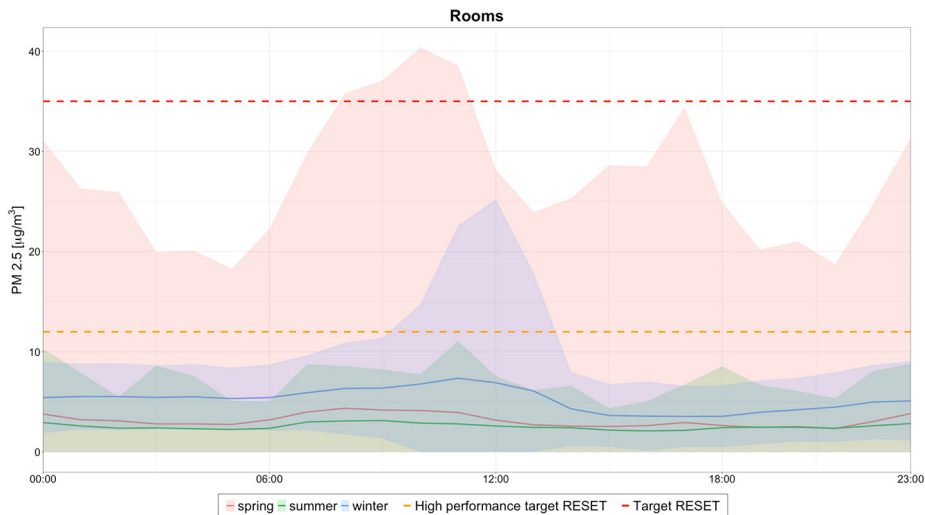

Figure 3.
Typical day pattern for the guestrooms for PM 2.5, seasonal differentiation
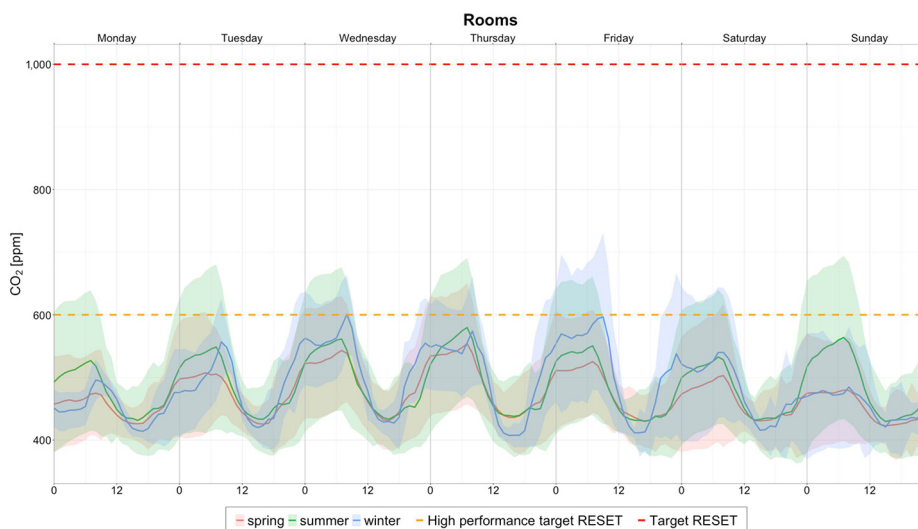
IJCHM

Figure 4.
Typical week pattern for the guestrooms for CO2, seasonal differentiation

5. Discussion and conclusions

5.1 Conclusions

The present study developed an overarching framework for studying IAQ in hospitality premises and applied it to a set of environmental and IAQ parameters of an hotel, monitored for more than six months. This approach allowed us to evaluate the impact of the air treatment system currently in place, alongside human activities, outdoor pollution, COVID-19-related restrictions and seasonality in different areas of the hospitality premise. In this way, we generated valuable insights in terms of both the drivers of IAQ and the opportunity to optimize the hotel's operations. From guests' perspective, a proper communication of how IAQ is monitored, analyzed and certified may improve the customer experience (Chang *et al.*, 2021) by quantitatively substantiating the perception of a clean and healthy environment (Magnini and Zehrer, 2021; Tiong *et al.*, 2021). With guests gaining a heightened awareness of air quality, this issue is altering people's orientation toward different destinations (Zhang *et al.*, 2020) and becoming a recurrent element in reviews (Villeneuve and O'Brien, 2020). Thus, hospitality venues may be able to leverage investments in air quality as a competitive advantage (Chang *et al.*, 2020).

5.2 Theoretical implications

This is the first study in the hospitality literature to develop an overarching framework for the investigation of IAQ. Differently from previous examples (Asadi *et al.*, 2011), we do not propose a framework for conducting a spot auditing of IAQ, but rather a comprehensive set of techniques for systematically analyze the IAQ on hospitality premises, both in terms of status quo and drivers. Our results suggest that a uniform research approach can be applied to various sites and produce more generalized conclusions for the sector. In this sense, the introduction of the RESET standard as a reference for both implementing and monitoring a network dedicated to IAQ performance (Zanni *et al.*, 2021) allows to overcome the fragmentation of existing research methodologies (Chang *et al.*, 2021). It also boost the recognizability and, consequently, credibility of IAQ information disclosed (Sharma *et al.*, 2020).

Compared to prior literature, our study covers the longest period and the highest sampling frequency with an innovative, real-time monitoring network.

We incorporate IAQ into the management's control dashboard, in line with a hospitality 5.0 approach (Pillai *et al.*, 2021), with the aim of fostering green decision-making, both on the organization's and customers' side. Within the organization, the communication of IAQ performance may contribute to the development of proenvironmental psychological capital in personnel and promote eco-friendly behaviors (Saeed *et al.*, 2019). Our framework allows to verify to what extend these conditions actually improve the overall environmental performance, offering quantitative reference to theoretical standpoints defined by extant literature in the field (Afsar *et al.*, 2020; Raza and Khan, 2022). As IAQ information can be also included into hotel communication, it conveys to customers the commitment of the organization toward eco-innovation practices (Sharma *et al.*, 2020), as well as their value. First, based on the cognitive consistency theory, the increased interest toward the topic is expected to drive the choice toward organizations committed to IAQ management and support the intention to return of customers (Aksu *et al.*, 2021; Bravo *et al.*, 2019). Second, in line with the servicescape framework (Bitner, 1992), the disclosure of information on IAQ performance through smart technologies may enhance the perception of service quality and improve the guests' experience (Mao *et al.*, 2018; Villeneuve and O'Brien, 2020; Xiong *et al.*, 2020; Zhou *et al.*, 2014). This is particularly relevant considering the pandemic and postpandemic era, as it provides concreteness of the results of cleaning operations and safety protocols (Aksu *et al.*, 2021; Jeong *et al.*, 2022; Wong *et al.*, 2022).

5.3 Practical implications
We substantiated our framework through a real-scale application and thereby generated insights for the management. First, we conducted our investigation on a hospitality premise with a full-scale, top-notch air treatment system. This allowed us to evaluate whether such a system provides an IAQ that generally aligns with expectations, displaying lower levels of indoor air pollution compared to empirical results reported by the extant literature (Chang *et al.*, 2021). For the guestrooms, the long-time series allowed us to extend the IAQ study proposed by Chang *et al.* (2020): We primarily evaluated the conditions of room occupation, when unpredictable activities also took place, as well as the IAQ of unoccupied rooms. For the kitchen and restaurant, we were able to study the service hours as well as the cleaning and rest periods, thereby expanding upon prior studies in terms of both time (Lee *et al.*, 2001) and incorporated air pollutants, namely, PM 2.5 and VOC (Chang *et al.*, 2021; Ott *et al.*, 2017; Wallace and Ott, 2011). Notably, this effort also allowed us to verify whether the IAQ results justify the voluntary investment in the air treatment system's implementation and maintenance. In the context of the COVID-19 pandemic, the level of awareness toward IAQ has increased dramatically, triggering the hotel management's interest and investment in this direction. That said, it is crucial to create a solid basis for performance assessment to promote long-term maintenance.

Second, we systematically identified the different drivers of IAQ – both exogenous (such as the changing seasons and outdoor pollution) and endogenous (such as specific activities performed in the different monitored areas, such as cooking or cleaning). Regarding the former, we clearly identified that outdoor air pollution influences IAQ in those areas where the two interact. In line with prior studies (Asadi *et al.*, 2011; He *et al.*, 2016), we verified that outdoor air quality does impact the IAQ of areas that are in contact with the outdoors (such as the hall, lobby and restaurant) and more subject to natural ventilation, or in places connected to the outside through a high ventilation rate (such as the kitchen). On the other hand, and in line with Chang *et al.* (2020), we verified that the IAQ in guestrooms is scarcely

affected by the outdoor air pollution, but instead responds to the activities performed in the room. The framework proposed is applicable regardless of the contour conditions, in terms of climate and season, thus transferrable in the hospitality sector worldwide, as the integration of the rich set of parameters monitored and the analyses applied allows to cope for possible local effects. The interpretation of results, though, needs necessarily to be contextualized considering the specificities of the local climate and sources of contamination, to draw proper insights for the managers.

Regarding the endogenous drivers, the IAQ study highlighted the most appropriate measure for limiting the exposure of both staff and guests to air pollution. For example, unoccupied guestrooms displayed an IAQ completely in line with the RESET standards, regardless of the internal fittings, furniture or exposure of the rooms. The concerning levels of contamination detected in guestrooms at an episodic level were directly related to the activities performed in the room, both by guests themselves and cleaning staff. Regulations against smoking on hospitality premises have certainly improved the IAQ results compared to previous field studies (Chan *et al.*, 2009), but the new vaping technologies may generate remarkable levels of VOCs, thereby producing material for future studies that are similar to Li *et al.* (2021). Moreover, the study of contamination peaks allowed us to verify the system's reaction to the stresses generated by human activities and the recovery time needed to ensure a proper IAQ for the next guest. With this information, one can adjust the schedule of cleaning operations to match the recovery period in standard conditions, or perhaps improve the ventilation to accelerate the process and limit pollution events. Even in the absence of critical exposure conditions, as in our case, the pandemic emergency (Kumar and Morawska, 2019) justifies equipping the hotel staff with personal protective devices during the cleaning operations (as done in Chang *et al.*, 2020).

Finally, we captured the impact of COVID-19-related measures on IAQ, both in terms of space occupation and direct effects. On the one hand, the pandemic restrictions affected guest behaviors by shifting their habits and limiting their presence on working days in the early months of 2021, as testified by the trends across periods. During the summertime, amidst the ease on restrictions, customers (including both business guests and tourists) progressively returned to a more typical use of the hotel premises. The impact of COVID-19-related measures was also clearly visible in the peaks of specific contaminants (i.e. VOC), which derived from advanced disinfection procedures (apparent through both fitness center tests and the guestroom cleaning schedule). Allowing the IAQ to recover before check-in time addresses a major concern by limiting conditions for the virus to spread from one guest to the next (Melikov *et al.*, 2020; Morawska *et al.*, 2020); therefore, facility managers should make this a priority target. Moreover, these elements may support the postpandemic recovery by equipping the hospitality management with monitoring tools that can be used to remotely assess cleaning operations and optimize their schedule (Pillai *et al.*, 2021).

5.4 Limitations and future research
The study presents some inherent limitations, which suggest pathways for future research. First, our applied monitoring methodology excluded a check of the microbial pollution in indoor air, which would have required active spot testing. Considering the relevance of the topic within the pandemic crisis, this would represent a valuable integration to the framework proposed. Second, our seasonal tests of the environmental and IAQ parameters only encompassed a single year. While the collected data supported our conclusions, it would be useful to confirm the results further by monitoring for multiple years. Third, the overlaps between changing seasons and COVID-19-related restrictions did not allow us to properly capture the relative magnitude of their effects, except in relationship to the use of

hotel areas and guest habits. Finally, the framework proposed could benefit from the validation on a broader set of premises, possibly presenting different features, in terms of architecture, areas usage, ventilation conditions and geographical contexts.

Future research could focus on two possible pathways. On the one hand, research efforts should be posed in deepening the analysis of the relationship between insights provided by IAQ monitoring and display and the commitment to take sustainability-oriented actions, both by organizations and customers. For organization, such impact can be envisaged into a modification of their management practices. For customers, the commitment should be studied in terms of choice, willingness to pay and satisfaction.

On the other hand, future studies could elaborate more on the opportunities provided by integrating IAQ information systems with control dashboards. For instance, facility managers could optimize their energy efficiency measures as well as operational schedules related to, e.g. cleaning routines. With regard to COVID management, IAQ monitoring could support the integrated risk assessment of areas based on occupation and activities performed (Kampezidou *et al.*, 2021). Such information might lead to a set of smart measures for promptly reacting to possible new epidemics or crises (Chan *et al.*, 2021; Sigala, 2020; Wut *et al.*, 2021).

References

Afsar, B., Maqsoom, A., Shahjehan, A., Afridi, S.A., Nawaz, A. and Fazliani, H. (2020), "Responsible leadership and employee's proenvironmental behavior: the role of organizational commitment, green shared vision, and internal environmental locus of control", *Corporate Social Responsibility and Environmental Management*, Vol. 27 No. 1, pp. 297-312.

Aksu, A., Albayrak, T. and Caber, M. (2021), "Hotel customer segmentation according to eco-service quality perception: the case of Russian tourists", *Journal of Hospitality and Tourism Insights*, Vol. 5 No. 3, pp. 501-514, doi: 10.1108/jhti-10-2020-0188.

Asadi, E., Costa, J.J. and Gameiro da Silva, M. (2011), "Indoor air quality audit implementation in a hotel building in Portugal", *Building and Environment*, Vol. 46 No. 8, pp. 1617-1623.

Bitner, M.J. (1992), "Servicescapes: the impact of physical surroundings on customers and employees", *Journal of Marketing*, Vol. 56 No. 2, pp. 57-71.

Bo, M., Mercalli, L., Pognant, F., Cat Berro, D. and Clerico, M. (2020), "Urban air pollution, climate change and wildfires: the case study of an extended Forest fire episode in Northern Italy favoured by drought and warm weather conditions", *Energy Reports*, Vol. 6, pp. 781-786.

Bourdrel, T., Annesi-Maesano, I., Alahmad, B., Maesano, C.N. and Bind, M.A. (2021), "The impact of outdoor air pollution on covid-19: a review of evidence from in vitro, animal, and human studies", *European Respiratory Review*, Vol. 30 No. 159, pp. 1-18.

Bravo, R., Martinez, E. and Pina, J.M. (2019), "Effects of service experience on customer responses to a hotel chain", *International Journal of Contemporary Hospitality Management*, Vol. 31 No. 1, pp. 389-405.

Carlisle, A.J. and Sharp, N.C.C. (2001), "Exercise and outdoor ambient air pollution", *British Journal of Sports Medicine*, Vol. 35 No. 4, pp. 214-222.

Carslaw, D.C. and Ropkins, K. (2012), "Openair – an r package for air quality data analysis", *Environmental Modelling and Software*, Vols 27/28, pp. 52-61.

Chan, J., Gao, Y.(L.) and McGinley, S. (2021), "Updates in service standards in hotels: how COVID-19 changed operations", *International Journal of Contemporary Hospitality Management*, Vol. 33 No. 5, pp. 1668-1687.

Chang, H. (S.), Huh, C., Legendre, T.S. and Simpson, J.J. (2020), "Exploring particulate matter pollution in hotel guestrooms", *International Journal of Contemporary Hospitality Management*, Vol. 32 No. 3, pp. 1131-1162.

Chang, H. (S.), Capuozzo, B., Okumus, B. and Cho, M. (2021), "Why cleaning the invisible in restaurants is important during COVID-19: a case study of indoor air quality of an open-kitchen restaurant", *International Journal of Hospitality Management*, Vol. 94, p. 102854.

Chan, E.S.W. and Hsu, C.H.C. (2016), "Environmental management research in hospitality", *International Journal of Contemporary Hospitality Management*, Vol. 28 No. 5, pp. 886-923.

Chan, W., Lee, S.C., Li, D. and Chen, X.Q.K. (2017), "Cigarette induced PM2.5 in hotel rooms: an assessment of the effectiveness of management's mitigating measures", *International Journal of Hospitality Management*, Vol. 60, pp. 42-47.

Chan, W., Lee, S.-C., Hon, A., Liu, L., Li, D. and Zhu, N. (2015), "Management learning from air purifier tests in hotels: experiment and action research", *International Journal of Hospitality Management*, Vol. 44, pp. 70-76.

Chan, W., Lee, S.C., Chen, Y., Mak, B., Wong, K., Chan, C.S., Zheng, C. and Guo, X. (2009), "Indoor air quality in new hotels' guest rooms of the major world factory region", *International Journal of Hospitality Management*, Vol. 28 No. 1, pp. 26-32.

Chan, E.S.W., Okumus, F. and Chan, W. (2020), "What hinders hotels' adoption of environmental technologies: a quantitative study", *International Journal of Hospitality Management*, Vol. 84, p. 102324.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R. and Feigin, V. (2017), "Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015", *The Lancet*, Vol. 389 No. 10082, pp. 1907-1918.

Dėdelė, A. and Miškinytė, A. (2016), "Seasonal variation of indoor and outdoor air quality of nitrogen dioxide in homes with gas and electric stoves", *Environmental Science and Pollution Research*, Vol. 23 No. 17, pp. 17784-17792.

El Kenawy, A.M., Lopez-Moreno, J.I., McCabe, M.F., Domínguez-Castro, F., Peña-Angulo, D., Gaber, I.M., Alqasemi, A.S., Al Kindi, K.M., Al-Awadhi, T., Hereher, M.E. and Robaa, S.M. (2021), "The impact of COVID-19 lockdowns on surface urban heat island changes and air-quality improvements across 21 major cities in the Middle east", *Environmental Pollution*, Vol. 288, p. 117802, doi: 10.1016/j.envpol.2021.117802.

Fang, G.C., Lo, C.T., Zhuang, Y.J., Cho, M.H., Huang, C.Y., Xiao, Y.F. and Tsai, K.H. (2017), "Seasonal variations and sources study by way of back trajectories and ANOVA for ambient air pollutants (particulates and metallic elements) within a mixed area at Longjing, Central Taiwan: 1-year observation", *Environmental Geochemistry and Health*, Vol. 39 No. 1, pp. 99-108.

Feinberg, S., Williams, R., Hagler, G.S., Rickard, J., Brown, R., Garver, D., Harshfield, G., Stauffer, P., Mattson, E., Judge, R. and Garvey, S. (2018), "Long-term evaluation of air sensor technology under ambient conditions in Denver, Colorado", *Atmospheric Measurement Techniques*, Vol. 11 No. 8, pp. 4605-4615.

Gao, M., Liu, W., Wang, H., Shao, X., Shi, A., An, X., Li, G. and Nie, L. (2021), "Emission factors and characteristics of volatile organic compounds (VOCs) from adhesive application in indoor decoration in China", *Science of the Total Environment*, Vol. 779, p. 145169.

Gigerenzer, G. (2004), "Mindless statistics", *The Journal of Socio-Economics*, Vol. 33 No. 5, pp. 587-606.

Hänsel, S., Ustrnul, Z., Łupikasza, E. and Skalak, P. (2019), "Assessing seasonal drought variations and trends over Central Europe", *Advances in Water Resources*, Vol. 127, pp. 53-75.

He, Q., Song, Q., Yan, Y., Wang, Z., Guo, L. and Wang, X. (2016), "Exposure to particle matters and hazardous volatile organic compounds in selected hot spring hotels in Guangdong, China", *Atmosphere*, Vol. 7 No. 4, doi: 10.3390/atmos7040054.

Jeong, M., Kim, K., Ma, F. and DiPietro, R. (2022), "Key factors driving customers' restaurant dining behavior during the COVID-19 pandemic", *International Journal of Contemporary Hospitality Management*, Vol. 34 No. 2, pp. 836-858.

Jiang, Y. and Wen, J. (2020), "Effects of COVID-19 on hotel marketing and management: a perspective article", *International Journal of Contemporary Hospitality Management*, Vol. 32 No. 8, pp. 2563-2573.

Kampezidou, S.I., Ray, A.T., Duncan, S., Balchanos, M.G. and Mavris, D.N. (2021), "Real-time occupancy detection with physics-informed pattern-recognition machines based on limited CO_2 and temperature sensors", *Energy and Buildings*, Vol. 242, p. 110863.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C. and Engelmann, W.H. (2001), "The national human activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants", *Journal of Exposure Science and Environmental Epidemiology*, Vol. 11 No. 3, pp. 231-252.

Kumar, P. and Morawska, L. (2019), "Could fighting airborne transmission be the next line of defence against COVID-19 spread?", *City and Environment Interactions*, Vol. 4 No. 2019, p. 100033.

Lai, I.K.W. and Wong, J.W.C. (2020), "Comparing crisis management practices in the hotel industry between initial and pandemic stages of COVID-19", *International Journal of Contemporary Hospitality Management*, Vol. 32 No. 10, pp. 3135-3156.

Lee, S.C., Li, W.M. and Yin Chan, L. (2001), "Indoor air quality at restaurants with different styles of cooking in metropolitan Hong Kong", *Science of the Total Environment*, Vol. 279 Nos 1/3, pp. 181-193.

Lelieveld, J., Pozzer, A., Pöschl, U., Fnais, M., Haines, A. and Münzel, T. (2020), "Loss of life expectancy from air pollution compared to other risk factors: a worldwide perspective", *Cardiovascular Research*, Vol. 116 No. 11, pp. 1910-1917.

Li, Y. and Ma, W. (2021), "Photocatalytic oxidation technology for indoor air pollutants elimination: a review", *Chemosphere*, Vol. 280, p. 130667.

Li, L., Nguyen, C., Lin, Y., Guo, Y., Fadel, N.A. and Zhu, Y. (2021), "Impacts of electronic cigarettes usage on air quality of vape shops and their nearby areas", *Science of the Total Environment*, Vol. 760, p. 143423.

Liu, X., Jayaratne, R., Thai, P., Kuhn, T., Zing, I., Christensen, B., Lamont, R., Dunbabin, M., Zhu, S., Gao, J. and Wainwright, D. (2020), "Low-cost sensors as an alternative for long-term air quality monitoring", *Environmental Research*, Vol. 185, p. 109438.

Liu, H.Y., Schneider, P., Haugen, R. and Vogt, M. (2019), "Performance assessment of a low-cost PM 2.5 sensor for a near four-month period in Oslo, Norway", *Atmosphere*, Vol. 10 No. 2, doi: 10.3390/atmos10020041.

Liu, Y., Zhou, Y. and Lu, J. (2020), "Exploring the relationship between air pollution and meteorological conditions in China under environmental governance", *Scientific Reports*, Vol. 10 No. 1, pp. 1-11.

Magnini, V.P. and Zehrer, A. (2021), "Subconscious influences on perceived cleanliness in hospitality settings", *International Journal of Hospitality Management*, Vol. 94, p. 102761.

Mao, Z., Yang, Y. and Wang, M. (2018), "Sleepless nights in hotels? Understanding factors that influence hotel sleep quality", *International Journal of Hospitality Management*, Vol. 74, pp. 189-201.

Marquès, M. and Domingo, J.L. (2022), "Positive association between outdoor air pollution and the incidence and severity of COVID-19. A review of the recent scientific evidences", *Environmental Research*, Vol. 203, p. 111930.

Melikov, A.K., Ai, Z.T. and Markov, D.G. (2020), "Intermittent occupancy combined with ventilation: an efficient strategy for the reduction of airborne transmission indoors", *Science of the Total Environment*, Vol. 744 No. 2, doi: 10.1016/j.scitotenv.2020.140908.

Meo, S.A., Abukhalaf, A.A., Alomar, A.A., Alessa, O.M., Sami, W. and Klonoff, D.C. (2021), "Effect of environmental pollutants PM-2.5, carbon monoxide, and ozone on the incidence and mortality of SARS-COV-2 infection in ten wildfire affected counties in California", *Science of the Total Environment*, Vol. 757, p. 143948.

Morawska, L., Tang, J.W., Bahnfleth, W., Bluyssen, P.M., Boerstra, A., Buonanno, G., Cao, J., Dancer, S., Floto, A., Franchimon, F. and Haworth, C. (2020), "How can airborne transmission of COVID-19 indoors be minimised?", *Environment International*, Vol. 142, p. 105832, doi: 10.1016/j.envint.2020.105832.

Ott, W.R., Wallace, L.A., McAteer, J.M. and Hildemann, L.M. (2017), "Fine and ultrafine particle exposures on 73 trips by car to 65 non-smoking restaurants in the San Francisco Bay area", *Indoor Air*, Vol. 27 No. 1, pp. 205-217.

Paterson, C.A., Sharpe, R.A., Taylor, T. and Morrissey, K. (2021), "Indoor PM2.5, VOCs and asthma outcomes: a systematic review in adults and their home environments", *Environmental Research*, Vol. 202, p. 111631.

Pillai, S.G., Haldorai, K., Seo, W.S. and Kim, W.G. (2021), "COVID-19 and hospitality 5.0: redefining hospitality operations", *International Journal of Hospitality Management*, Vol. 94, p. 102869.

Pozzer, A., Dominici, F., Haines, A., Witt, C., Münzel, T. and Lelieveld, J. (2020), "Regional and global contributions of air pollution to risk of death from COVID-19", *Cardiovascular Research*, Vol. 116 No. 14, pp. 2247-2253.

Raza, S.A. and Khan, K.A. (2022), "Impact of green human resource practices on hotel environmental performance: the moderating effect of environmental knowledge and individual green values", *International Journal of Contemporary Hospitality Management*, Vol. 34 No. 6.

Saeed, B., Bin Afsar, B., Hafeez, S., Khan, I., Tahir, M. and Afridi, M.A. (2019), "Promoting employee's proenvironmental behavior through green human resource management practices", *Corporate Social Responsibility and Environmental Management*, Vol. 26 No. 2, pp. 424-438.

Sahu, V. and Gurjar, B.R. (2020), "Spatial and seasonal variation of air quality in different microenvironments of a technical university in India", *Building and Environment*, Vol. 185, p. 107310.

Setti, L., Passarini, F., De Gennaro, G., Barbieri, P., Perrone, M.G., Borelli, M., Palmisani, J., Di Gilio, A., Torboli, V., Fontana, F. and Clemente, L. (2020), "SARS-Cov-2RNA found on particulate matter of Bergamo in Northern Italy: first evidence", *Environmental Research*, Vol. 188, p. 109754.

Sharma, T., Chen, J. and Liu, W.Y. (2020), "Eco-innovation in hospitality research (1998-2018): a systematic review", *International Journal of Contemporary Hospitality Management*, Vol. 32 No. 2, pp. 913-933.

Sigala, M. (2020), "Tourism and COVID-19: impacts and implications for advancing and resetting industry and research", *Journal of Business Research*, Vol. 117, pp. 312-321.

Theuring, S., Thielecke, M., van Loon, W., Hommes, F., Hülso, C., von der Haar, A., Körner, J., Schmidt, M., Böhringer, F., Mall, M.A. and Rosen, A. (2021), "SARS-CoV-2 infection and transmission in school settings during the second COVID-19 wave: a cross-sectional study, Berlin, Germany, November 2020", *Eurosurveillance*, Vol. 26 No. 34, p. 34, doi: 10.2807/1560-7917.es.2021.26.34.2100184.

Theußl, S. and Zeileis, A. (2009), "Collaborative software development using R-forge. Special invited paper on 'the future of R'", *The R Journal*, Vol. 1 No. 1, pp. 9-14.

Tiong, Y.Y., Sondoh, S.L., Tanakinjal, G.H. and Iggau, O.A. (2021), "Cleaner operations in hotels: recommendation for post-pandemic green recovery", *Journal of Cleaner Production*, Vol. 283, p. 124621.

UNWTO (2020), "impact assessment of the covid-19 outbreak on international tourism", available at: www.unwto.org/impact-assessment-of-the-covid-19-outbreak-on-international-tourism

Villeneuve, H. and O'Brien, W. (2020), "Listen to the guests: text-mining Airbnb reviews to explore indoor environmental quality", *Building and Environment*, Vol. 169, p. 106555.

Wallace, L. and Ott, W. (2011), "Personal exposure to ultrafine particles", *Journal of Exposure Science and Environmental Epidemiology*, Vol. 21 No. 1, pp. 20-30.

Wei, W., Wargocki, P., Zirngibl, J., Bendžalová, J. and Mandin, C. (2020), "Review of parameters used to assess the quality of the indoor environment in green building certification schemes for offices and hotels", *Energy and Buildings*, Vol. 209, p. 109683.

WHO/Europe (2010), *WHO Guidelines for Indoor Air Quality: Selected Pollutants*, Puncto Druck+ Medien GmbH, Bonn, doi: 10.1186/2041-1480-2-S2-I1.

Wong, I.K.A., Huang, J., Lin, Z.(C.J.) and Jiao, H. (2022), "Smart dining, smart restaurant, and smart service quality (SSQ)", *International Journal of Contemporary Hospitality Management*, Vol. 34 No. 6, pp. 2272-2297, doi: 10.1108/IJCHM-10-2021-1207.

Wut, T.M., Xu, J.(B.) and Wong, S.M. (2021), "Crisis management research (1985–2020) in the hospitality and tourism industry: a review and research agenda", *Tourism Management*, Vol. 85, p. 104307.

Xie, R., Xu, Y., Yang, J. and Zhang, S. (2021), "Indoor air quality investigation of a badminton hall in humid season through objective and subjective approaches", *Science of the Total Environment*, Vol. 771, p. 145390.

Xiong, W., Huang, M., Okumus, B. and Fan, F. (2020), "Rethinking sleep quality in hotels: examining the risk and protective factors associated with travel-related insomnia", *International Journal of Hospitality Management*, Vol. 90, p. 102644.

Yang, Y., Zhang, X. and Fu, Y. (2022), "Foreign tourists' experiences under air pollution: evidence from big data", *Tourism Management*, Vol. 88, p. 104423.

Załuska, M. and Gładyszewska-Fiedoruk, K. (2020), "Regression model of PM2.5 concentration in a single-family house", *Sustainability (Switzerland)*, Vol. 12 No. 15, p. 5952, doi: 10.3390/su12155952.

Zanni, S., Motta, G., Mura, M., Longo, M. and Caiulo, D. (2021), "The challenge of indoor air quality management: a case study in the hospitality industry at the time of the pandemic", *Atmosphere*, Vol. 12 No. 7, p. 880, doi: 10.3390/atmos12070880.

Zhang, X., Yang, Y., Zhang, Y. and Zhang, Z. (2020), "Designing tourist experiences amidst air pollution: a spatial analytical approach using social media", *Annals of Tourism Research*, Vol. 84, p. 102999.

Zhong, S., Yu, Z. and Zhu, W. (2019), "Study of the effects of air pollutants on human health based on baidu indices of disease symptoms and air quality monitoring data in Beijing, China", *International Journal of Environmental Research and Public Health*, Vol. 16 No. 6, p. 1014, doi: 10.3390/ijerph16061014.

Zhou, X., Lian, Z. and Lan, L. (2014), "Experimental study on a bedside personalized ventilation system for improving sleep comfort and quality", *Indoor and Built Environment*, Vol. 23 No. 2, pp. 313-323.

Ziliak, S.T. and McCloskey, D.N. (2004), "Size matters: the standard error of regressions in the American economic review", *The Journal of Socio-Economics*, Vol. 33 No. 5, pp. 527-546.

Appendix

Table A1.
Environmental and IAQ parameters in the different areas monitored, in terms of mean value and SD, along the whole period

Area	n. obs.	T (°C) (SD)	RH (%) (SD)	CO_2 (ppm) (SD)	PM 2.5 ($\mu g/m^3$) (SD)	VOC (ppm) (SD)
Hall	53,196	23.46 (2.06)	44.73 (15.51)	446.36 (29.75)	4.12 (5.53)	163.00 (148.87)
Lobby	53,419	23.08 (1.10)	44.15 (14.52)	446.61 (28.03)	1.65 (3.76)	100.89 (48.47)
Kitchen	53,418	25.51 (2.37)	38.80 (12.70)	443.76 (27.40)	2.77 (3.58)	118.14 (179.13)
Restaurant	53,352	24.31 (1.75)	41.50 (13.52)	442.22 (30.10)	2.25 (2.98)	121.44 (102.11)
Fitness center	53,351	24.63 (2.78)	40.77 (12.50)	448.78 (32.22)	2.96 (2.51)	188.33 (522.44)
Guest rooms	1,265,177	22.74 (1.87)	46.40 (16.33)	478.24 (89.02)	2.98 (17.99)	129.94 (318.82)

Table A2.
Environmental and IAQ parameters in the different areas monitored, in terms of mean value and SD, across seasons

Area	Season	n. obs.	T (SD)	RH (SD)	CO2 (SD)	PM 2.5 (SD)	VOC (SD)
Hall	Winter	2,496	22.65 (1.89)	33.91 (4.34)	462.05 (38.48)	16.17 (8.16)	190.82 (266.56)
	Spring	26,806	22.99 (2.00)	33.88 (11.43)	446.31 (25.84)	4.79 (5.94)	183.97 (170.09)
	Summer	23,894	24.07 (1.98)	58.03 (8.13)	444.78 (32.24)	2.11 (1.38)	136.57 (90.53)
Lobby	Winter	2,496	22.76 (0.59)	33.97 (2.95)	467.42 (38.86)	7.26 (11.14)	123.59 (53.30)
	Spring	26,852	23.31 (1.11)	32.90 (9.73)	447.28 (28.18)	1.72 (3.59)	108.57 (51.51)
	Summer	24,071	22.86 (1.08)	57.75 (4.94)	443.71 (25.44)	0.99 (0.71)	89.98 (41.47)
Kitchen	Winter	2,496	26.31 (1.71)	28.28 (3.33)	467.78 (38.90)	6.22 (3.48)	138.52 (189.85)
	Spring	26,854	25.81 (2.55)	29.36 (8.41)	445.53 (28.20)	2.77 (3.77)	131.27 (201.75)
	Summer	24,068	25.09 (2.15)	50.42 (5.66)	439.26 (23.21)	2.42 (3.15)	101.39 (146.81)
Restaurant	Winter	2,445	24.22 (1.21)	31.33 (3.11)	459.93 (38.84)	6.87 (7.39)	140.67 (160.79)
	Spring	26,849	24.63 (1.96)	31.23 (9.32)	439.86 (26.02)	2.28 (3.05)	130.20 (103.22)
	Summer	24,058	23.96 (1.46)	53.99 (4.85)	443.05 (32.58)	1.76 (1.16)	109.70 (91.33)
Fitness center	Winter	2,497	22.06 (1.02)	34.36 (3.78)	474.22 (44.34)	6.87 (3.38)	136.18 (302.13)
	Spring	26,851	23.18 (2.08)	32.64 (10.01)	451.94 (31.89)	2.41 (2.07)	163.12 (444.95)
	Summer	24,003	26.52 (2.37)	50.53 (7.77)	442.60 (29.13)	3.17 (2.46)	221.96 (611.21)
Guest rooms	Winter	54,705	22.83 (2.19)	33.59 (4.78)	481.40 (85.46)	5.22 (6.59)	113.14 (148.35)
	Spring	635,259	22.84 (1.85)	33.90 (9.83)	470.72 (77.61)	3.16 (24.86)	129.68 (393.48)
	Summer	575,213	22.61 (1.85)	61.42 (7.97)	486.24 (99.79)	2.56 (4.96)	131.82 (224.63)

Table A3.
Regression of PM 2.5 into guestrooms ($R^2 = 0.0402$)

$PM25_i$	Coeff.	St. error	T	$P > |t|$	95% confidence interval	
$PM25_0$	0.052984	0.020042	2.64	0.009	0.013414	0.092553
_cons	2.204396	0.38009	5.8	0	1.453995	2.954797

Area	VOC hourly peaks	Registered occupations	Correspondence (%)
Room A	69	73	95
Room B	113	117	97
Room C	50	55	91
Room D	79	152	52
Room E	59	63	94
Room F	22	26	85
Room G	87	90	97
Room H	98	102	96
Room I	76	77	99
Room J	62	65	95
Room K	197	206	96
Room L	53	55	96
Room M	73	76	96
Room N	78	83	94
Room O	143	148	97
Room P	194	204	95
Room Q	142	143	99
Room R	20	28	71
Room S	105	115	91
Room T	147	149	99
Room U	69	77	90
Room V	174	194	90
Room W	102	108	94
Room X	14	16	88

Table A4.
Number of registered
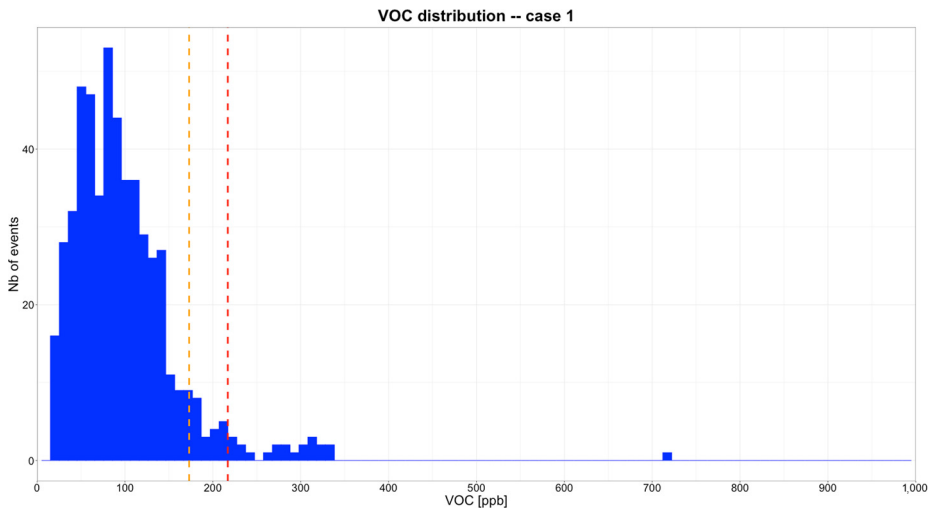guestrooms
occupations and
VOCs hourly peaks

Figure A1.
Distribution of
pollution events at
check-in time

Corresponding author
Sara Zanni can be contacted at: sara.zanni7@unibo.it